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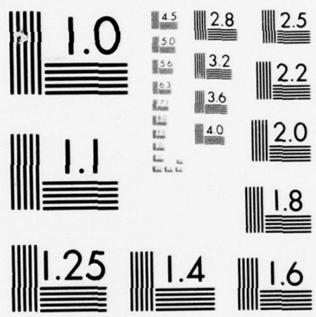

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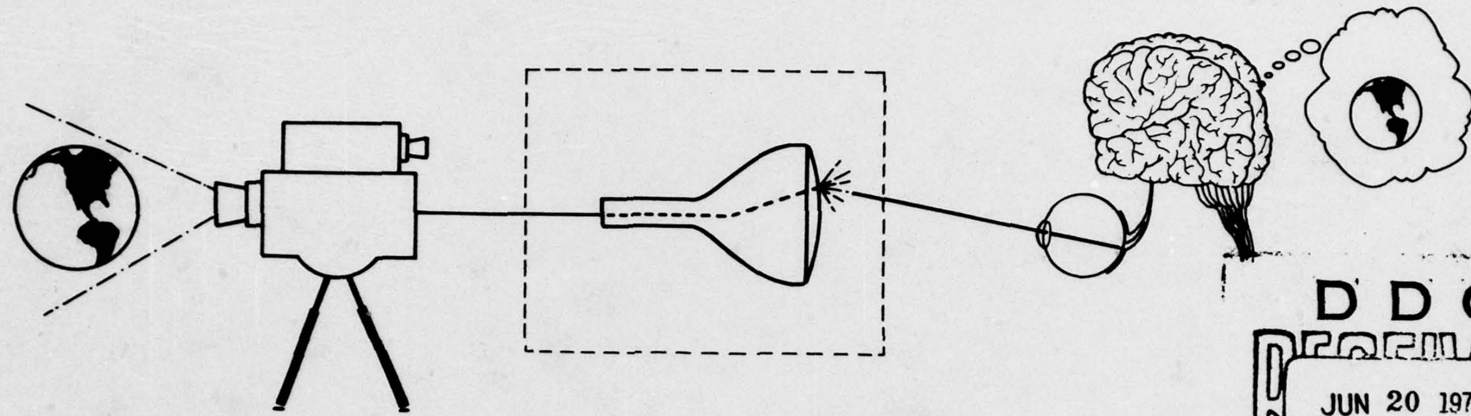

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DESIGN CRITERIA FOR IMAGING SENSOR DISPLAYS

W. L. Carel, J. A. Herman, and L. A. Olzak

October 1977

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This handbook provides essential theoretical and empirical data useful in the optimization of displays of sensor imagery. It considers the perceptual and information processing limitations of the human observer and presents recommended design approaches to meeting these needs. A new theoretical basis for the degrading effects of vibration on human visual performance is proposed which serves to reconcile previous data.

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PREFACE

The avowed policy of the United States is the maintenance of peace through military advantage. In a world of technical evolution, this policy is implemented in the form of a program of continuous improvement in military systems effectiveness. Constant attention must be given to increasing the surveillance and response capacities of such systems to ensure that the strategic balance remains favorable. Response decisions must be made on the basis of information gathered from ever-increasing standoff ranges under more challenging environmental conditions.

In response to this need, mechanisms which extend the decision maker's own senses over long distances and into new regions of the energy spectrum are being refined. But the collection of information through the agency of these artificial sensors does not in itself guarantee that such data can be fully available for exploitation. The data must be presented to the decision maker in a form that preserves the critical military significance while conforming to the capabilities and limitations of the observer's own capacity to perceive and to process information. In many instances, it has been found that this objective is best accomplished by reconstructing a visual image of the surveyed region on an imaging display.

To the degree that the system designer has successfully identified and packaged the critical sensed information in conformance with the abilities of the observer to perceive and to process it, the system potential to complete its intended function is enhanced. The problem of optimizing this information link is not straightforward, however, and the considerations that lead to an optimized design have not been succinctly summarized. It is the purpose of this report to review some of the more important factors in the design of imaging sensor displays so that the designer may gain a better understanding of the constraints and criteria affecting the optimization of these systems.

Before proceeding to the examination of the intensity/spatial factors in display optimization, let us briefly set the design process in perspective by discussing the functional context in which displays are used.

A major consideration in the optimization of a display system not discussed here because of the open-ended nature of its effect is the mission/task application of the

display/observer system. Obviously, all of the factors we discuss in this report must be weighed in the context of these functional objectives.

We make no pretense that this report is a comprehensive guide to the design of imaging displays. We hope, however, that we have concentrated information of a useful nature and thereby have made a useful contribution to the display optimization process.

Robert S. Jacobs, PhD.
Program Manager

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1.0 BACKGROUND AND INTRODUCTION

W. L. Carel
Senior Scientist
Hughes Aircraft Co.

The information presented in this report is the result of an extended program of empirical and analytical data collection by specialists in display hardware development and in human perception. Although a great many factors may influence the performance of the imaging display to human viewer communication link, we have limited ourselves herein to those that have been demonstrated to be most important in terms of magnitude of effect while also most manipulatable through careful design.

We have organized the material into three logical subdivisions according to the nature of the factors considered; intensity/spatial factors, temporal factors, and environmental factors affecting the design of imaging displays. In each section, we summarize what is known about the way these influences affect the display/observer communication process and suggest appropriate design strategies for dealing with them.

In an appendix, we present a computerized approach to the evaluation of display quality based upon recently published work by Task and Verona. This model considers some of the factors identified in the spatial/intensity section of the report, but needs further work to incorporate temporal and environmental effects.

1.1 HOW SENSOR DISPLAYS ARE USED

The operator's primary task in using a real time sensor display that maps the ground is to find and classify operationally significant targets and landmarks in the time available. Because the lobe of sharp visual acuity is on the order of 4 degrees (typically smaller than that subtended by the display) the observer searches the display with a sequence of fixations at a nominal rate of three fixations per second until something of interest is sighted. The candidate target is then examined foveally and classified or rejected. This process may be more fully described under the rubric of visual search, detection, and recognition.

1.1.1 Search

The observer's visual search strategy will be dictated by a priori information, by contextual information, by the ratio of the target size to the ground

area displayed, by the amount of ground area displayed, by the display type (moving scene vs. static) and by time available. The appearance on the display of easily recognized landmarks whose coordinates with respect to the target are known, will rapidly direct the operator's visual scan to the target area. If, for example, the target is a bridge over the confluence of two small rivers and the observer can see the rivers on the display, he will know where the bridge is even if it is not imaged. Should the observer know that a target is in a certain area without knowing exactly where, this knowledge will cause him to restrict his search to the relevant area. A priori information about the context in which the target is located produces an effect both generic and powerful. Contextual information is provided by the field of view or scope of the sensor and by the natural distribution of landmarks in the environment.

While context provides information on likely areas to be scanned — one expects to find boats on rivers — context can also have a detrimental effect on the operator's ability to find the target. If landmarks are not unique but are similar in size and appearance to the target, they will form a cluttered background in which the target lies embedded. This is the classic problem of "the number of alternatives" discussed by several authors who have conducted recognition research using artificial geometric figures. An example of the effects of background clutter and target size on search time using photographic and IR imagery of the real world are shown in Figure 1-1.

When time available is limited, it is the ground area displayed rather than display size or scale that determines the probability of fixating and finding the target. Increasing the size of the display beyond that required for the operator to see all the sensed information may only increase his search time, for

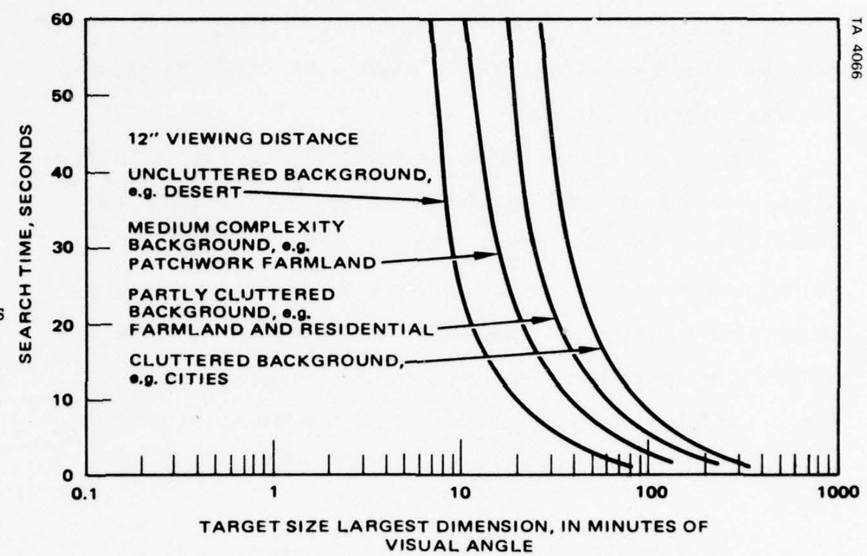


Figure 1-1. Search time as a function of background clutter and target size.

no new information is provided and a larger display must be scanned. An increase in the ground area scanned, however, will increase the amount of information the operator must process per unit time and he will adapt his search strategy to these demands. The probability of fixating the target will remain constant when displayed ground area is proportional to time available.

Display type will also affect the observer's search strategy. The scan used for stationary displays is determined by the mission needs and the image characteristics but appears almost haphazard with many fixations at the center. Moving displays such as IR and radar line scanners as well as FLIR and TV systems used in aircraft are scanned at the leading edge of the information. This results in a more systematic time-paced search strategy that sometimes results in a greater probability of locating the target. The operator will cease search either when the target is seen or located by deduction from context.

1.1.2 Detection

Detection by the operator may be said to occur when the target yields a consistent image whose displayed size and contrast exceeds the visual threshold. The factors that limit detection are those that contribute to the displayed visual subtense and contrast of the target, i.e., the size and modulation of the imaged target coupled with the threshold limits of the eye.

Estimates of the threshold limits of the eye may be derived from classical psychophysical data. Conditions that are sub-threshold will not result in detection, although the observer may know perfectly well where the target is on contextual grounds. Conversely, there is no guarantee that supra-threshold conditions will result in detection for the operator must not only look directly at the target but also decide that the local image element is a signature rather than a noise pulse.

Detection criteria are only appropriate for objects against a uniform background like the sky or sea, for simple detection implies only that the observer has decided that there is something out there that is different than system noise. When the background itself is a melange of objects, as is the case when searching most terrain types, a different process is implied. Field data have shown that detection of ground objects in a "busy" context occurs almost simultaneously with recognition. The reason is that an observer will not claim to detect a specific object — a truck — unless he has already decided that it is in fact at least a vehicle rather than a bush. This implies more than classical detection and means

that the operator has already decided that the object is a candidate target. He will do this because the sensor resolution permits the discrimination of the class of objects to which the target belongs. For example, when asked to find a radar van embedded in a natural background in a TV image, the operator will claim to detect it when the definition is such that about eight visible TV lines (four optical lines) are laid across the target. He will not at that point be able to tell whether it is a radar van, a truck, a jeep, a tank, an artillary gun, or a troop carrier. Thus the process of detection in this context implies a level of perceptual discrimination more complex than simple classical detection. The primary variable contributing to this process is the definition of the target as seen by the observer.

1.1.3 Recognition

It is a truism that even an imaged blob may be classified correctly if sufficient context is present; an observer may rightly infer that an undifferentiated blob on the end of the runway is an aircraft. It is also a truism that such inferences may be false and a system that yields finer grain data will both increase the confidence that can be placed in the judgment and permit a higher level discrimination. By finer grain data is meant increased definition, i.e., more visually discernible sensor lines across the target. Increased definition is generally achieved by a sensor with better ground resolution coupled with a display system carefully matched to the observer's eye. As more information is supplied by the sensor-display system, less reliance has to be placed on a priori data and fewer risks have to be taken in classification. Definition suitable for deciding that a target is a non-background object — detection — is only marginally suitable for classifying the object as, say, a vehicle. Still more definition is required to determine whether a vehicle is a tank, an APC, or a farm truck, and still more to discriminate between a Soviet and an American tank. Hypothetical relationships among definition, the level of classification, and the probability that the classification is correct, are shown in Figure 1-2.

From this brief discussion it is apparent that there is more than one way to find a target on a sensor display. At one extreme the location of the target can be found even if it is not imaged on the display if its coordinates are known, other prominent landmarks are imaged, and the observer brings much a priori information to the situation. Indeed this is often the case in the use of conventional radar; training, navigation, timing, and the use of well

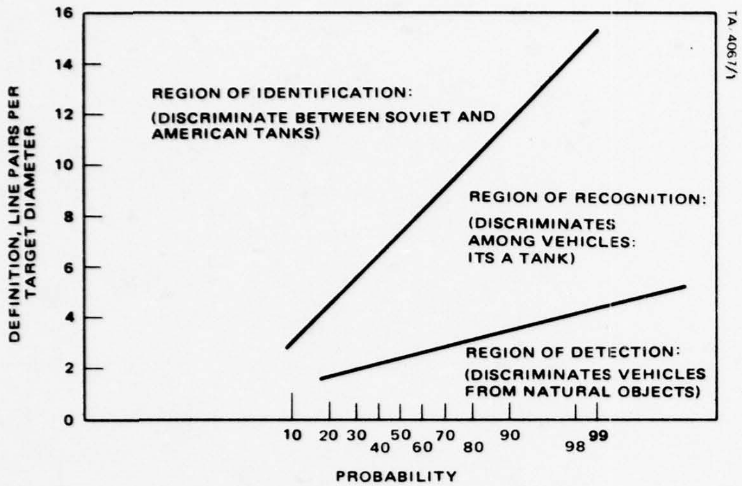


Figure 1-2. Probability of detection and recognition as a function of definition.

imaged offset aim points compensate for the sometimes poor quality of the radar image. At the other extreme are sensors such as television, some of which yield extremely high resolution. These sensors provide a unique shape signature so sharply defined and well-modulated that even the most naive observer could describe the imaged object. One is tempted to speculate that the amount of information involved in deciding that one has found a target is the same in both these instances, except that in the one case the bulk of the information is brought to the situation by the observer and in the other case is supplied by the sensor/display system.

1.2 THE ADVENT OF THE MULTIPURPOSE CRT DISPLAY

For tactical aircraft the day of the display dedicated to a single sensor is rapidly coming to a close. In the next decade, it will be common to have television, infrared, and radar systems as the sensor complement on board a relatively small, tactical aircraft. There is not enough cockpit real estate to allow each sensor the privilege of a dedicated display and the irreversible trend, therefore, is toward multi-function display systems where the same monitor can be time-shared to present video data from any of the on-board ground mapping sensors. The trend is also converging towards the common format of a raster scanned cathode ray tube monitor, scan converted where necessary as is the case with radar data. The television-like image of the raster CRT is likely to be the final interface between any of the sensors and the observer.

The consequence of this is that the same display must satisfy not only all the input sensors but also the various strategies used by the operator to find and classify targets. The most stringent requirement generally evolves from its highest resolution sensor, that sensor which yields high target definition and subtle modulation.

2.0 INTENSITY AND SPATIAL FACTORS IN IMAGING SENSOR DISPLAY DESIGN

Walter L. Carel
Senior Scientist
Hughes Aircraft Co.

2.1 INTRODUCTION

Information is represented on the face of a cathode ray tube by a spatially arrayed pattern of light of varying intensity. The performance potential of a display/observer communication link will reflect the degree to which the spatial and intensity characteristics of the displayed information conform to the perceptual needs of the observer. In this chapter, some of the design decisions that effect this match are considered.

2.2 OPTIMIZING DYNAMIC RANGE

When mounted in a tactical aircraft, the cathode ray tube has had a long 20 year battle trying to overcome the effects of sunlight. For decades, the displays had neither enough luminance nor enough contrast to operate effectively in high ambients. This problem is by no means solved today.

Cathode ray tube phosphors reflect about 70 percent of the ambient light. With an ambient of 2000 fL due to sky light, the phosphor luminance is therefore 1400 fL with no signal at all. With a "black level" of 1400 it is difficult to produce enough additional luminance for good display dynamic range. The typical solution to this problem is to use filters. For tactical aircraft displays that must be viewed from varying angles, the most promising filters are the neutral density filter and the "notched filter. The neutral density filter achieves the purpose of ncreasing the display contrast ratio or dynamic range by attenuating the ambient light before it impinges on the phosphor and again after it is reflected from the phosphor into the eye of the observer. The light emitted by the CRT is attenuated only once. Thus, the "black level" of the 70 percent phosphor in a 2000 fL ambient with a 10 percent neutral filter is 2000 x 0.1 x 0.7 x 0.1 = 14 fL. The notched filter provides an additional gain by carefully matching the spectral pass band of the filter to the spectral characteristics of the phosphor. In this way, all the ambient light outside the pass band is further reduced and a large portion of the luminance energy produced by the emitter is passed to the eye

of the observer. A more complete description of these two types of filters and how they may be used to optimize display dynamic range follows*.

The general contrast enhancement technique using two way attenuation is shown in Figure 2-1. An optical chain (a series of contrast enhancement elements) is mounted in front of a CRT. The first surface of the optical chain reflects r_f** of the ambient light which strikes it, and transmits a fraction T of the light passing through it. The phosphor reflects r_p of the light which hits it. The signal output at the phosphor is L_{CRT}.

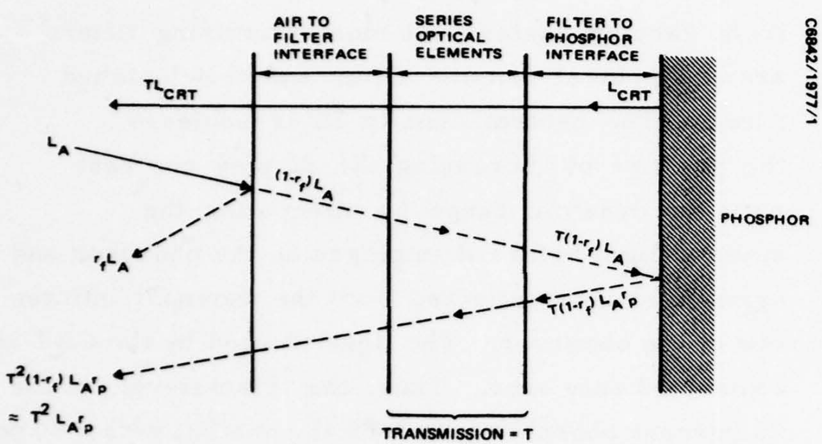


Figure 2-1. Optical chain.

The SIGNAL/BACKGROUND RATIO (S/B) presented to the viewer is:

$$S/B = \frac{L_{SIGNAL}}{L_{BACKGROUND}} \tag{1}$$

The signal the viewer sees is:

$$L_{SIGNAL} = T \times L_{CRT}$$

The BACKGROUND 'noise' is the sum of the first surface and secondary reflections:

$$L_{BACKGROUND} = r_fL_A + T^2 (1 - r_f) L_A r_p$$

---

*This derivation is taken, in part, from an earlier report published by this laboratory, "Highly Reliable Vertical Display System, Phase II," Hughes Aircraft Company, dated May 1974.

**r_f = First surface reflection if optical interfaces are properly matched.

Generally, $r_f << 1$ (Typically $r_f = 0.005$ to 0.01). Then:

$$L_{BACKGROUND} = L_A \left(r_f + T^2 r_p \right)$$

Substituting in (1) and simplifying:

$$S/B = \frac{L_{CRT}}{L_A} \left(\frac{1}{\frac{r_f}{T} + Tr_p} \right) \qquad (2)$$

Figure 2-1 shows that the BACKGROUND LEVEL transmitted to the viewer consists of two components. The first component ($r_f L_A$) reflects directly from the front surface. The second component ($T^2 L_A r_p$) is the ambient, attenuated twice after passing through the attenuator-filter and being reflected back from the phosphor. Equation 2 shows that the first surface reflectivity (r_f) is essentially amplified by $1/T$, and the phosphor reflectivity (r_p) is effectively attenuated by T (normalized for the CRT surface).

To minimize the first component, the first surface reflectivity must be reduced to the smallest extent possible. However, practical considerations make about 0.5 percent the lowest figure obtainable. Dust, fingerprints, dirt, combine to increase the reflectivity, thus increasing the magnitude of the first component of noise. The r_f term will always exist, but it can be reduced to a fraction of a percent.

The second component of BACKGROUND, $T^2 L_A r_p$, can theoretically be reduced to zero by making T very small. However, a small transmission will also attenuate the CRT signal, so that the resulting display brightness will be so far below the eye's adaptation level that it will be unusable. So, a compromise must be achieved in reaching an attenuation which is optimum for a given situation. Both r_f and r_p are constants determined by the characteristics of the system. Both must be minimized and T must be optimized to obtain the maximum S/B for a given r_f and r_p.

Examination of Equation (2) shows that S/B is a maximum, when r_f and r_p are minimized. To find the maximum S/B for a given r_f and r_p, we differentiate (2) with respect to T and set equal to zero:

$$\frac{d}{dt}(S/B) = \frac{d}{dT}\left[\frac{L_{CRT}}{L_A} \left(\frac{1}{\frac{r_f}{T} + Tr_p} \right) \right]$$

$$= -T^{-2} r_f + r_p = 0$$

or;

$$T_{opt} = \sqrt{\frac{r_f}{r_p}} \qquad (3)$$

T_{opt} = optimum transmission to obtain a maximum S/B for a given r_f and r_p. T is independent of the ambient and CRT brightness and $T \leq 1$.

The maximum S/B obtainable can then be found by substituting T_{opt} into (2):

$$S/B\ MAX = \frac{L_{CRT}}{L_A} \frac{1}{\frac{r_f}{\sqrt{\frac{r_f}{r_p}}} + (r_p)\sqrt{\frac{r_f}{r_p}}}$$

$$S/B\ MAX = \frac{L_{CRT}}{L_A} \frac{1}{2\sqrt{r_f r_p}}$$

The term used in this analysis, signal to background ratio, was chosen for convenience in analysis and does not represent the true constant ratio, or dynamic range of the display. Dynamic range is defined as: L_{max}/L_{min}, in the preceding formulation, $L_{signal} + L_{background}/L_{background}$; thus $L_{max}/L_{min} = S/B + 1$. The expression $\frac{1}{2\sqrt{r_f r_p}}$ is an index of $C.R._{max}$ when T is optimum and L_{CRT}/L_{AMB} is constant. A plot of r_f versus T_{opt} with r_p as a parameter is shown in Figure 2-2. Along each of these curves select values of $\frac{1}{2\sqrt{r_f r_p}}$ are annotated. From this plot is is evident that r_f is the

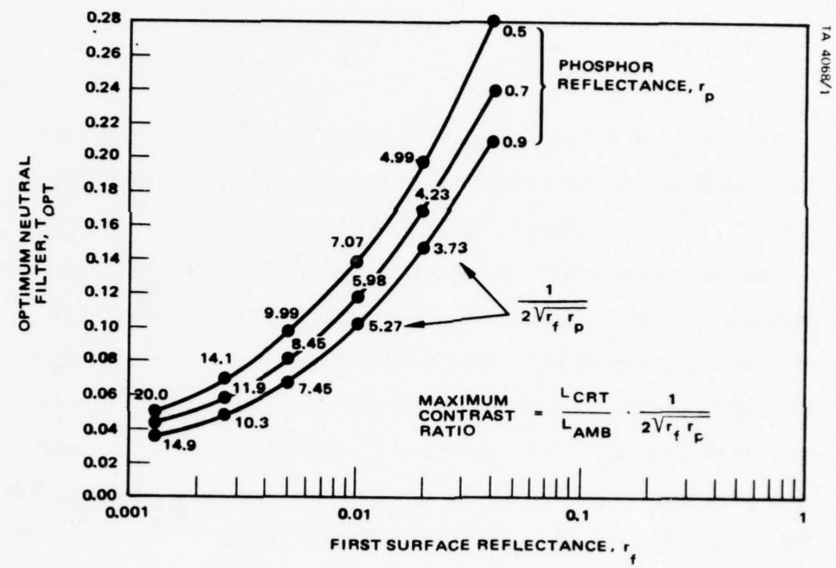


Figure 2-2. Optimum neutral filter for various combinations of phosphor and reflectance.

critical characteristic and that unless r_f (first surface reflection) is less than 1 percent, the display will be washed out and of low contrast.

Using $(1/(r_f/T + T_{rp}))$ from equation (2) as an index of contrast efficiency we have plotted in Figure 2-3 the effects of r_f and T for a fixed value of r_p. When r_f is high no value of T does much good. When r_f is extremely low, say 0.001, contrast efficiency is very sensitive to filter selection and peaks at a value of about T = 0.06. At typical r_f values of 0.005, contrast is maximum when T is on the order of 0.09.

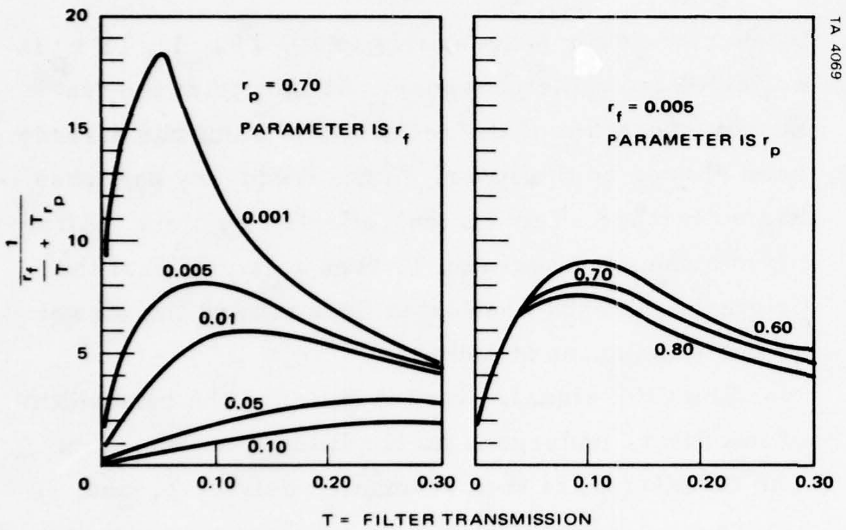


Figure 2-3. Two way filter.

In Figure 2-3, a similar plot of contrast efficiency as a function of r_p and T with r_f at a value of 0.005 is presented. The curves are nearly parallel and for the values of r_p 0.6 to 0.8 typical of most phosphors peak at a T of about 0.10.

2.2.1 Restrictive Bandwidth (Notched Filter)

The restrictive bandwidth filter passes all those frequencies within its own passband and attenuates those frequencies outside its passband. When combined with a narrowband phosphor as shown in Figure 2-4, the phosphor/matched filter combination provides a narrowband light output to the viewer.

The normal light-adapted-eye responds to the curve labelled photopic response, peaking at 555 millimicrons (green). By absorbing all of the ambient light under the unshaded portion of the curve, and

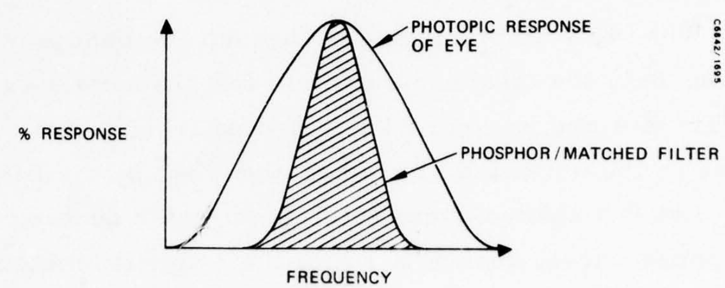


Figure 2-4. Narrowband phosphor/filter.

presenting useful information at only those frequencies under the shaded curve to the viewer, the effects of ambient light are reduced in direct proportion to the ratio of the areas under the two curves.

The analysis which follows is based on this assumption that the contrast ratio observed by the eye is proportional to the normalized ratio of the energy emitted by the CRT to the total energy under the photopic-response curve. The validity of this assumption has been indirectly verified by lab tests.

As shown in Figure 2-5, ambient light, L_A, strikes the air filter interface. $r_f L_A$ is reflected back toward the viewer. At this point, all the light within the photopic eye passband illustrated below is passed through the interface. (The light outside the photopic eye passband is not considered since the eye does not respond to these wavelengths, unless their magnitude is excessive.)

When this ambient passes through the bandpass filter, only the frequencies within the shaded area of Figure 2-4 are passed. The rejected frequencies, those in the unshaded area, are absorbed by the filter.

Let F = shaded area/Total area under photopic response curve, then $F \times L_A$ of the original ambient light energy passes through the bandpass filter. The

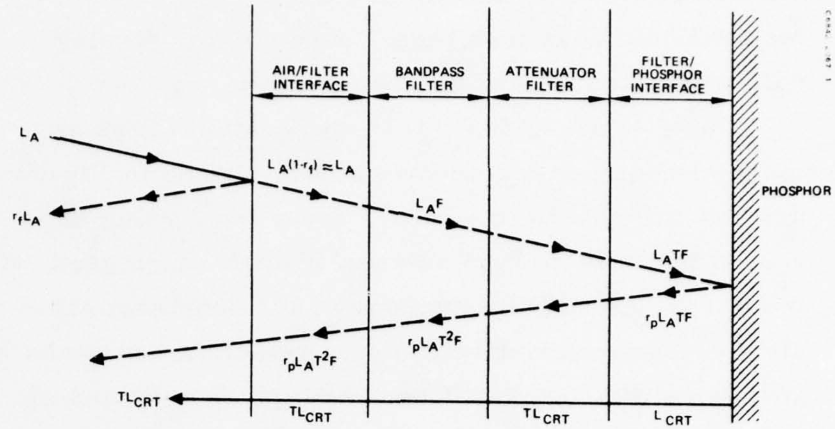


Figure 2-5. Bandwidth restriction optical chain.

attenuator-filter reduces this to L_A TF. $L_A TF r_p$ is reflected from the phosphor. At this point the frequency spectrum of the reflected ambient has already been shaped by the filter, so the frequency bandpass has no further effect on the reflected ambient. After being attenuated again by T, then $r_p L_A T^2 F$ of the original ambient is reflected back toward the viewer as one component of noise.

The CRT signal, since it matches the bandwidth of the filter, undergoes no bandwidth compression. The CRT signal is then attenuated only by T, and emerges as a signal of $T L_{CRT}$. Then

$$\text{SIGNAL/BACKGROUND Ratio} = \frac{T\,L_{CRT}}{r_f L_A + r_p L_A T^2 F}$$

$$S/B = \frac{L_{CRT}}{L_A}\,\frac{1}{\frac{r_f}{T} + r_p TF} \tag{4}$$

in this equation, r_f, r_p and F are constants fixed by hardware constraints.

Again, to find the maximum contrast ratio, differentiate, set equal to zero, and solve for T.

$$-\frac{r_f}{T^2} + r_p F = 0$$

$$\frac{r_f}{F r_p} = T^2$$

$$T = \sqrt{\frac{r_f}{F r_p}}$$

Substitute T into (4)

$$S/B\ MAX = \frac{L_{CRT}}{L_A}\,\frac{1}{\frac{r_f}{\sqrt{\frac{r_f}{F r_p}}} + r_p\sqrt{\frac{r_f}{F r_p}}\,F}$$

$$S/B\ MAX = \frac{L_{CRT}}{L_A}\,\frac{1}{2\sqrt{F r_f r_p}}$$

Thus, bandwidth compression technique improves contrast ratio by $1/\sqrt{F}$, over and above that obtained for two-way attenuation (see Figure 2-6).

In summary, the options available to the designer to optimize the display contrast ratio are the characteristics of the first surface reflection, r_f; of the phosphor reflection, r_p; of the display luminance, L_{CRT}; of the filter transmission, T, and of the spectrum of the filter, F. Analysis demonstrates that reduction of first surface r_f reflection is of paramount importance. Raising the luminance of the CRT generally has the effect of decreasing the

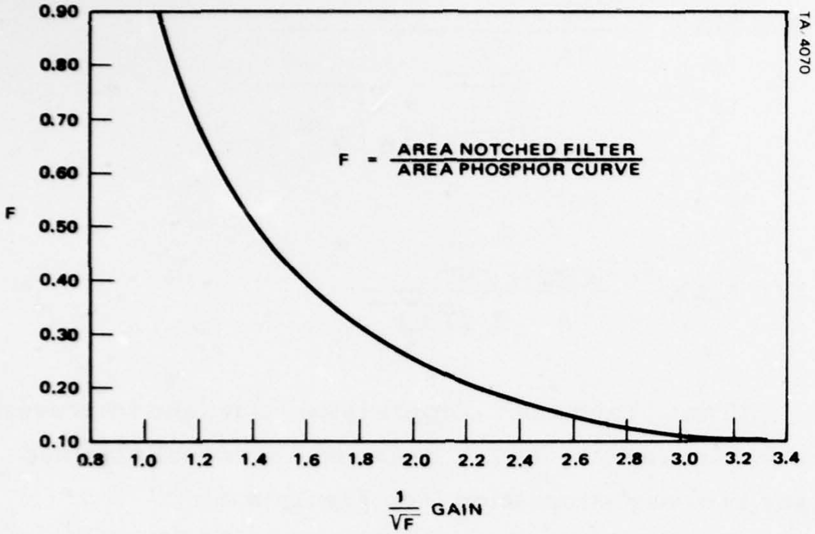


Figure 2-6. Gain and dynamic range due to matched filter and phosphor.

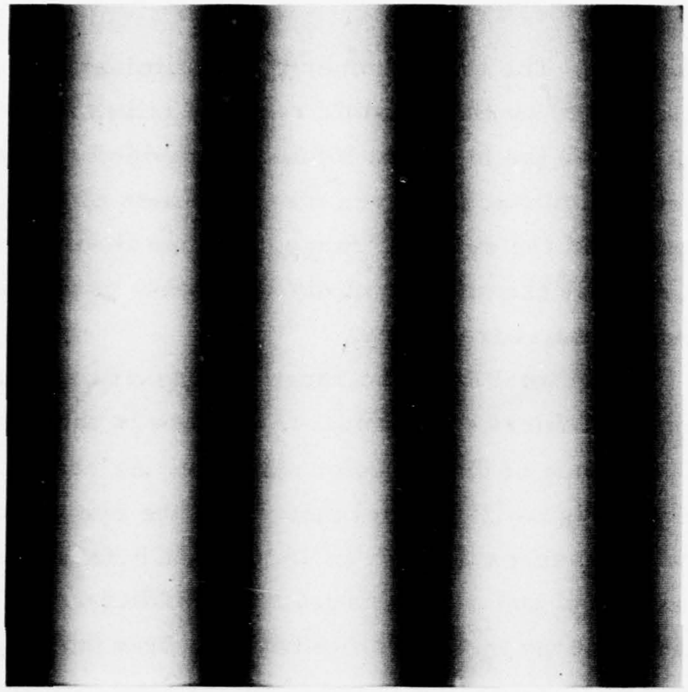
resolution by spreading the spot size which is to be avoided. The most likely way of improving contrast ratio then, is by choice of filter. If the system is designed to optimize contrast ratio, e.g., $L_{max}/L_{min} = CR_{max}$, then the formulation provided in the preceding section can be used.

2.3 OPTIMIZING GRAY LEVEL COUNT

Optimizing the contrast ratio, however, may not be the best way of tailoring the display for the use of the observer. It has been argued that that display which is best yields the greatest number of discernible gray levels in the local region of a visual fixation. (Task and Verona, 1976)

The number of discernible gray levels will be regulated on the one hand by the limitations of vision and on the other hand by the characteristics of the display. The figure of merit to be developed in the following paragraphs accounts for both the observor and the display. We shall start with the observor.

One way of characterizing the capacity of vision is to utilize existing data describing the visual modulation sensitivity function (MSF). These data describe the modulation required for a pattern to be seen as the spatial frequency of the pattern is varied. Typical sinusoidal patterns used to determine modulation thresholds are illustrated in Figure 2-7. The sine wave pattern is in fact a repetitive series of gray levels with the "on" portion representing one level and the "off" portion the other.



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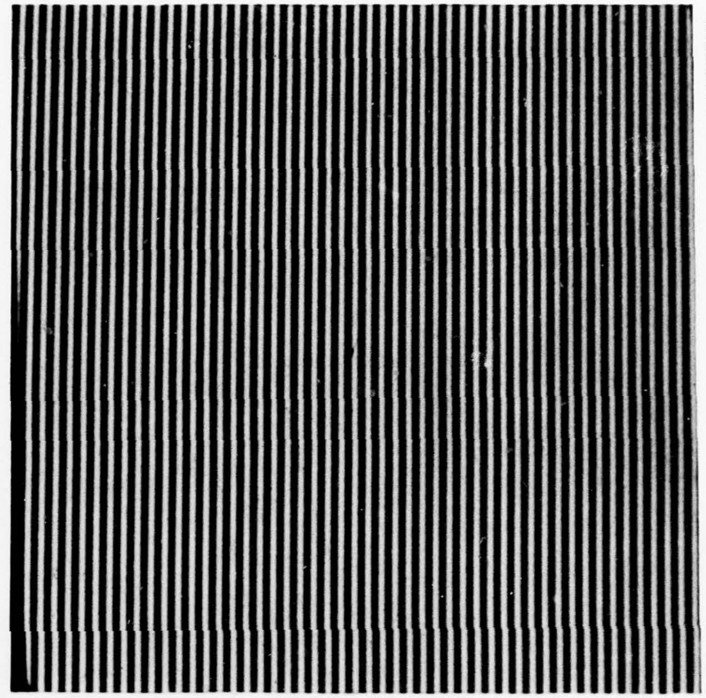

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Figure 2-7. Low and high frequency sinusoidal test patterns.

The modulation required to discriminate gray levels varies with the spatial frequency of the information, with the luminance level of the display, and with the visual adaptation match between the display luminance and the light level of the ambient. The shape of the visual modulation sensitivity function (MSF) for sine wave patterns is shown in Figure 2-8. The effects of adaptation mismatch are ignored in these figures. (For some spatial frequencies the sensitivity of the eye to a square wave pattern is about $4/\pi$ greater than the sensitivity to sine waves. That is, the threshold is slightly lower for square waves.) The MSF data inform us only of the modulation threshold; the modulation required to discriminate two gray

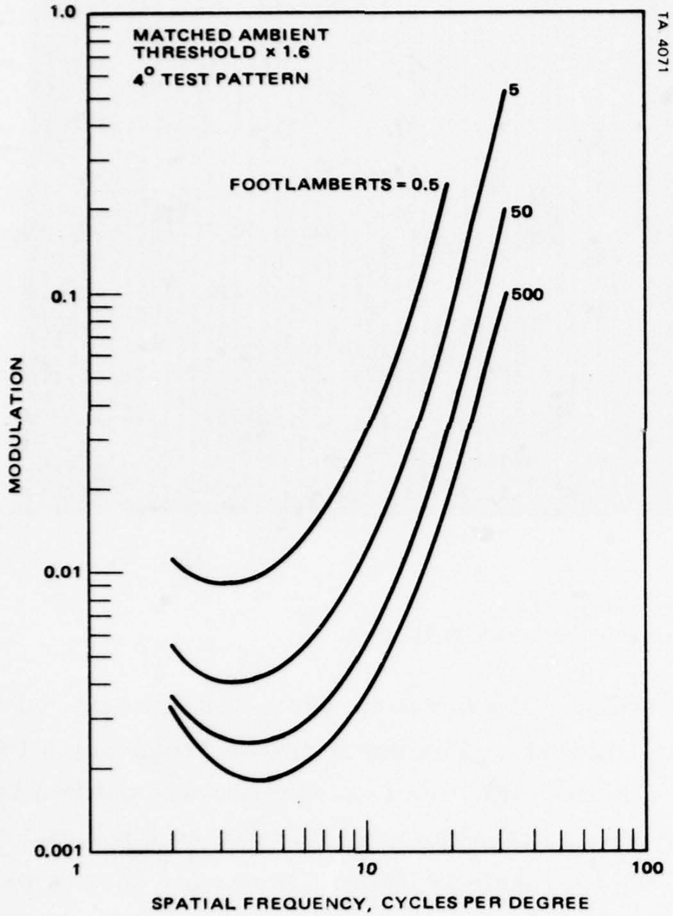

Figure 2-8. Representative MSF data (Rogers & Carel, 1973).

shades. The total number of discriminable gray shades is limited by the dynamic range of either vision or the display - the highlight luminance divided by the "black" level luminance. Given these two sets of data, the MSF and the dynamic range, one can theoretically calculate the number of discriminable gray shades at each spatial frequency.

The total dynamic range of vision is enormous if one considers the luminance of snow in the sun to the luminance of dust in faint starlight. As can be seen from Figure 2-9, (Stevens, 1960) the eye can respond to luminances as high as 16,000 ML before tolerance is exceeded and as low as 0.000001 ML before the luminance energy level becomes too low. This is a total dynamic range on the order of 10 billion to 1. However, Figure 2-9 also demonstrates that vision is a "two-channel" system; the photopic system appropriate for daylight and the scotopic for night. Because of the low acuity of scotopic vision, the use of displays driven at those low luminance levels for the extraction of detailed information is inappropriate. The region of interest then is photopic vision in which the total dynamic range exceeds 1 million to 1. Although the total dynamic range is large the instantaneous dynamic range is considerably less. The instantaneous range varies from 100:1 to 1000:1, and provides a window

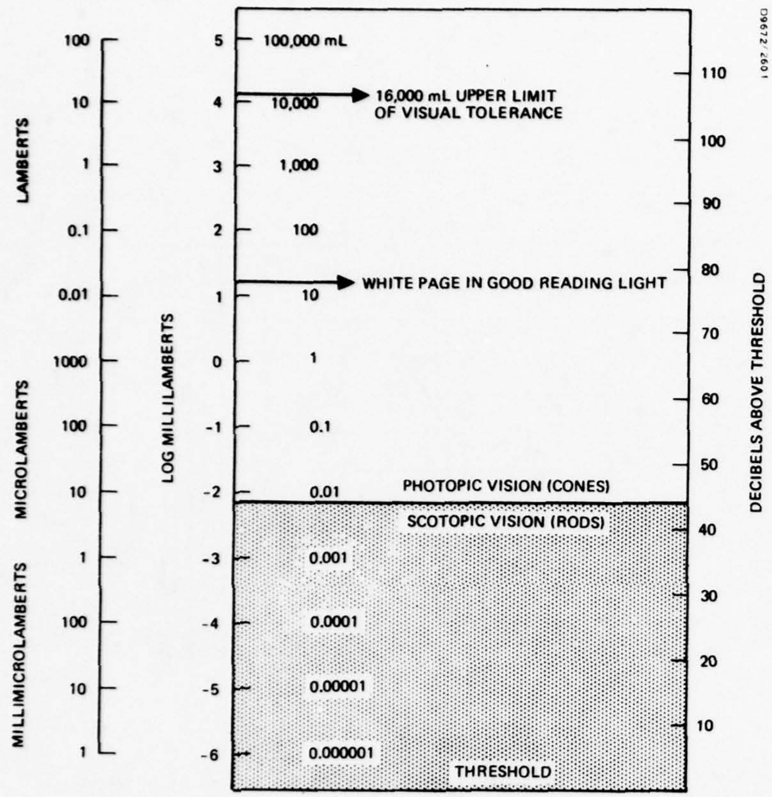

Figure 2-9. Range of light intensities that the human eye confronts. (Stevens, 1960)

of that size whose position is controlled by the visual adaptation level. If the eye, for example, is adapted to 1000 fL, then any luminance below 1 fL will appear black and no luminance discriminations can be made below that level.

This relatively small instantaneous dynamic range seems on examination to accommodate the range of luminances in the natural world. Jones and Condit (1949) measured the luminances of points within a variety of natural scenes and calculated a luminance scale for each scene. A luminance scale was defined as the ratio of the maximum to the minimum luminance; what we have called here dynamic range. A typical scene and sample data are reproduced in Figure 2-10 and Table II-1. Summary data plotting frequencies of occurrence of luminance scales is shown in Figure 2-11. In later studies Condit obtained scale values in excess of 1000 for some brilliant sunlit scenes.

Not included in these measurements of typical scenes are isolated local luminances due to specular reflection. Lustre, sheen, glints and sparkles are all due to specular reflection and those highlights provide considerable information about the structure of materials and the motion of objects. The quaking aspen and the sparkling sea are metaphors for the

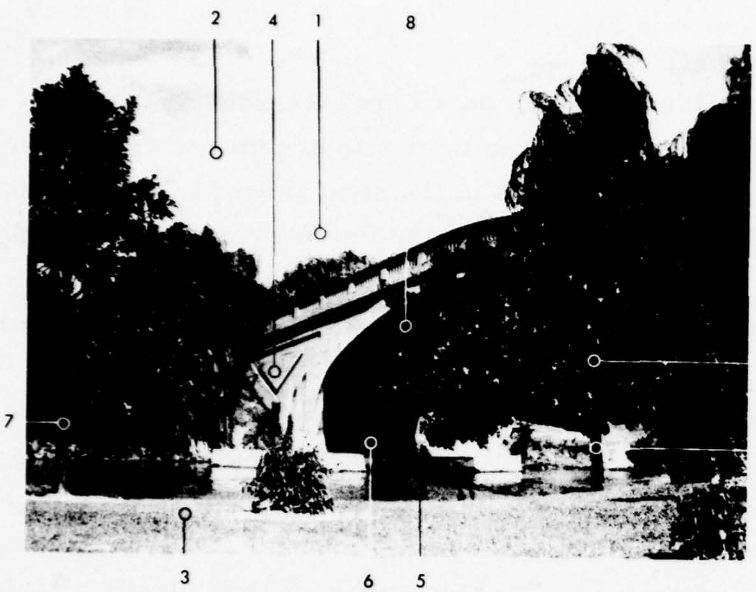

Figure 2-10. Landscape in which the luminances were measured (Mees and James, 1966).

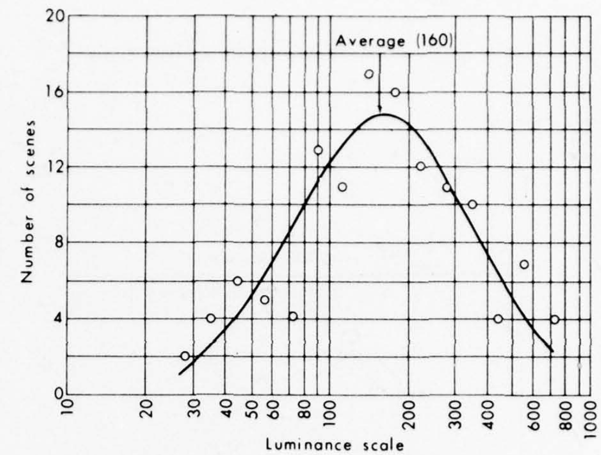

Figure 2-11. Frequency of occurrence of the luminance scales of the outdoor scenes (Mees & James, 1966).

Table II-1. Luminance Values in an Outdoor Scene (Mees and James, 1966)

Area No.	Description of Area	Luminance, ftL
1	White cloud	3500
2	Blue sky	1350
3	Grass	1000
4	Side of bridge in sun	800
5	Water in sun	460
6	Bridge in open shade	300
7	Tree trunk on left	135
8	Bridge in heavy shade	100
9	Tree trunk on right	33
10	Heavily shaded portion of tree	18
	Luminance scale of object	195

role of specular reflection. How much additional dynamic range is required to sense the luminance increment due to specular reflection is unknown.*

The teleological argument advanced in the preceding paragraphs might persuade us that an eye with an instantaneous dynamic range on the order of something less than 100-1 would serve quite well in our natural environment. Fortunately, we do not have to depend on an argument, for several authors have conducted the research that allows us to estimate the instantaneous dynamic range from measured empirical data.

Nutting (1916) determined the luminance that is just visible immediately after the eye has been adapted to a given luminance. This is in effect the instantaneous dynamic range of the eye. The results are shown in Figure 2-12. These data show, for example,

*It is interesting to note that specular reflection could be sensed in the color domain even if vision did not have sufficient dynamic range to accommodate the specular luminance increment. A perfect specular surface reflects the color of the illuminant rather than the color of the object and therefore provides color contrast. In nature very few things are perfectly specular and the "highlights" of objects are typically a mixture of the object color and the illuminant. However, this color difference in addition to the luminance "highlight" is enough to provide the necessary information. In black and white displays specular highlights are typically clipped because of limited display dynamic range and the brightness transfer function. In color displays the specular reflections are retained not because the display luminance range is greater, but because the reflections are carried by a color difference. This could be one of the great advantages of color in reproducing natural scenes - color enhances the perception of specular reflections and thus provide the viewer with information concerning the structure of materials and the movement of objects: the quaking aspen and sparkling sea.

that with a pre-adapting luminance of 10 ML, a luminance of 0.05 ML is required to pass the threshold, i.e., just above black. This represents an instantaneous dynamic range of 10/0.05 = 200:1. Similar data were gathered by Arbribat and Pitt, converted to dynamic range and replotted in Figure 2-12. Pitt provides a formula to determine subjective black for the middle range of adaptation levels:

$$\text{Log}_{10}L_S = 0.64\ \text{Log}_{10}L_0 - 1.9$$

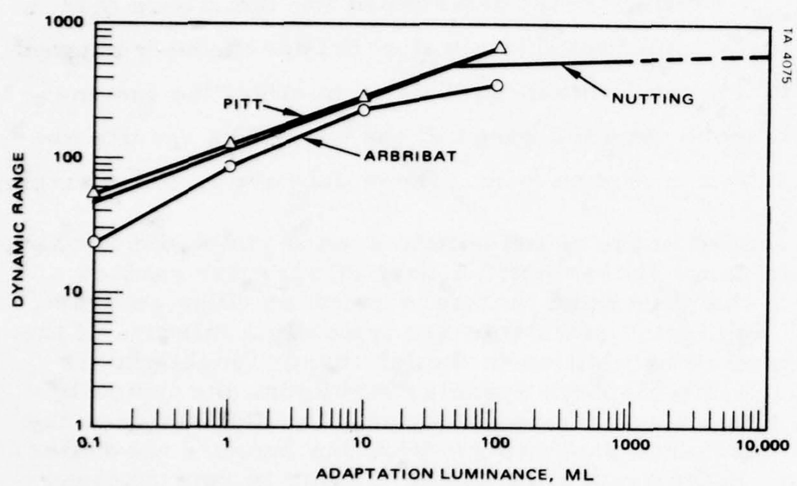

Figure 2-12. Visual instantaneous dynamic range as a function of adaptation luminance.

where L_S is subjective black and Lo is the adapting luminance.

These data show that at high daylight adaptation luminances, the visual dynamic range is on the order of 500:1, at dusk on the order of 100:1, and in the lower regions of photopic sensitivity on the order of 50:1. For purposes of further computation, the curve based on Pitt's formula corrected in the higher luminance regions by Nutting's data shall be used.

Given the instantaneous dynamic range and the modulation sensitivity function, the number of perceivable gray levels may be estimated. The visual modulation sensitivity function to be used in these analyses are the basic thresholds times a factor of 1.6. In the experiments from which the MSF data were taken, it was found that the modulation thresholds needed to be multiplied by a factor of 1.6 to reach a "comfortable" threshold. For practical use, it seems proper to use these higher threshold values and the thresholds times 1.6 will be used throughout this handbook when values for visual demand modulation are required.

"Comfortable" values of the MSF for a range of luminances are plotted in Figure 2-8. These data show, for example, that a frequency of 20 cycles per

degree and a luminance of 3000 cd/m^2 demands a modulation of 0.017 if the difference between two adjacent gray levels is to be discriminated. From Figure 2-12, which depicts the instantaneous dynamic range of the eye, we can estimate that the visual dynamic range is 550:1. If it is also assumed that the upper luminance level and adaptation level are identical at 3000 cd/m^2, then subjective black is 3000/550 = 5.45 cd/m^2 and all luminance values below 5.45 will appear equally black so that no further gray level discrimination can be made. What we want to do next is count the number of discernible gray levels, each increment of which demands a modulation of 0.017, over the dynamic range from 5.45 to 3000 cd/m^2. At the first approximation it is assumed that the demand modulation stays constant over the dynamic range. The process is graphically represented in Figure 2-13 and calculated from the expression:

$$\text{Gray Levels} = \frac{\text{Log}_{10} Z}{\text{Log}_{10}\left(1 + \frac{2M_D}{1 - M_D}\right)} + 1$$

where, Z = dynamic range
M_D = demand modulation.

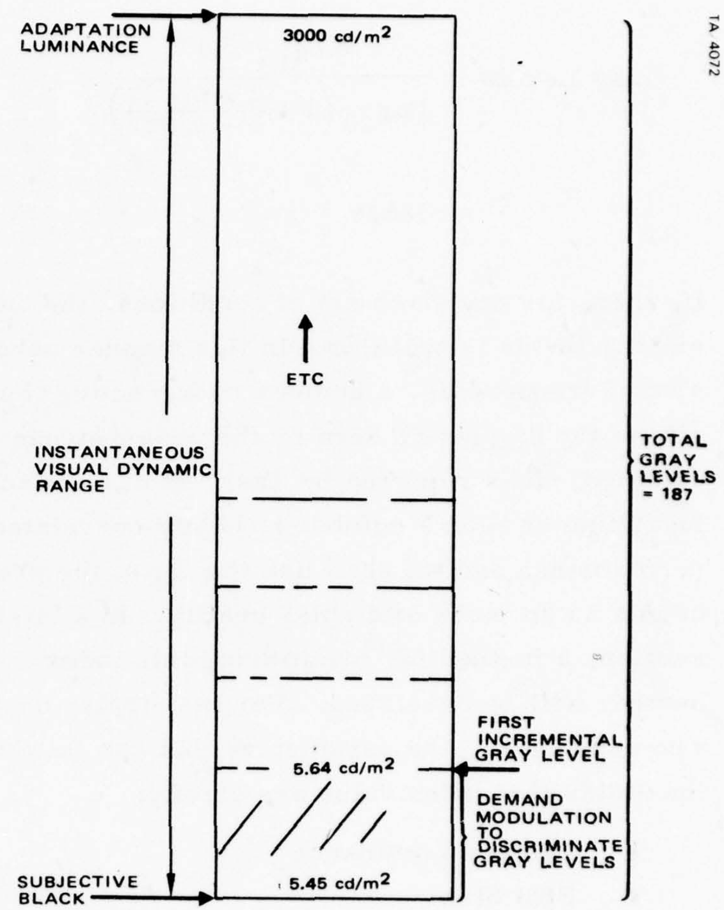

Figure 2-13. Number of perceivable gray levels at a spatial frequency of 20 cycles per degree and an adaptation level of 3000 cd/m^2.

In the example cited:

$$\text{Gray Levels} = \frac{\text{Log}_{10} 550}{\text{Log}_{10}\left(1 + \frac{2 \times 0.017}{1 - 0.017}\right)} + 1$$

$$= 186.6$$

If, then, for any given set of conditions, the number of gray levels is calculated in this manner across all spatial frequencies, a number representing the capacity of the display as seen by the observer can be obtained. It is reported by Task, et al, that the logarithm of such a number is highly correlated with performance and we shall use the log of the gray level counts as an index of display quality. In a later section, a method for maximizing this index number will be developed. For the display designer who uses CRTs, the parameters that can be varied to maximize that index value are chiefly:

- Display Luminance
- Spot Size
- Filter Choice

2.3.1 Luminance Quantization

Digital scan converters are increasingly used in sensor displays and one of their functions is to convert continuous video into a number of incremental steps. These appear on the display as steps in luminance. One problem for the designer is to decide the number of bits required to encode the video dynamic range. A basis for doing this is to provide a granularity sufficient to reproduce the input signal. Assuming that the A/D conversion is a linear process, it produces a binary output word whose value is linearly related to the magnitude of the sampled analog input voltage. Then if V_{min} is the minimum value of the input signal and V_{max} is the maximum signal value to be quantized;

$$V_{MAX} = 2^n V_{MIN} ,$$

where n is the number of A/D bits. The dynamic range of the video is given by definition as

$$K = 20 \log_{10} \frac{V_{max}}{V_{min}} = 20 \text{ n} \log_{10} 2 = 6.02 \text{ n (db)}.$$

The dynamic range of the A/D converter is equal to approximately 6 dB times the number of A/D conversion bits. This relationship is tabulated in Table II-2. Conventional television displays have

Table II-2. Dynamic Range as a Function of A/D Bits

n	Dynamic Range = K (dB)
1	6.02
2	12.04
3	18.04
4	24.08
5	30.10
6	36.12
k	6.02 k

dynamic ranges of 25 to 30 dB for example, thereby requiring 4 to 5 bits for encoding dynamic range.

Additional criteria for deciding the number of bits required for luminance quantization can be based on operator performance data in a target detection and recognition task or in a subjective evaluation of image quality where the number of quantization bits is varied.

If we look at a one-bit (2 gray levels) television picture of an oblique aerial scene, the image appears as a lithographic black and white print and it is very difficult to discern what is being seen. At two-bits (4 gray levels), the scene is recognizable, but marked by heavy contouring. It is easy to decide that such a coarse quantization is unsuitable for a spectrum of operational tasks. When the quantization is raised to three-bits (8 gray levels), there is a marked difference in the quality of the image, but homogeneous areas are still noticeably contoured. As the number of bits is raised through 4 and 5 the image takes on the continuous tone characteristic of analog imagery and by the time 8 bits are used (256 gray levels) it is impossible to tell the difference between an original scene and a quantized scene using even the most stringent observational criteria.

There have been a few studies which measure operator performance as a function of the number of gray level bits. In one such study, the operator was to find landmarks such as a road junction on high quality side-looking radar.

The operator was thoroughly briefed using aerial photographs before each trial so that he brought considerably a-priori information to the task. Results from a radar study are shown in Figure 2-14. From the data, it is apparent that the number of bits assigned to gray level contributed little to performance although the 2-bit case is marginally inferior. These kinds of results are typical of radar study results

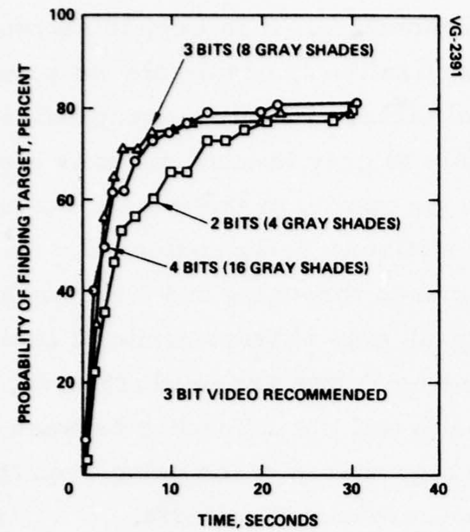

Figure 2-14. Effect of gray level quantization when the operator uses radar to find pre-briefed target.

which are remarkably resistant to changes in the characteristics of the display system. Part of the reason is undoubtedly because of the nature of the targets – fixed landmarks – and the amount of intelligence the operator brings to the task before the display is even turned on. A good operator can almost visualize what he will see and the radar image simply confirms that expectation in the large and in small detail. In such a situation, it is not too surprising that performance will remain constant – at least in the laboratory – in spite of large differences in display characteristics. It is also the case that radar imagery is relatively noisy compared to electro-optical imagery. The scintillation noise in the static pictures used in these studies was frozen in the imagery and gave the salt and pepper look characteristic of radar imagery. The result is that the noise spectrum broke up the contours that usually appear in insufficiently quantized imagery and the subjective objection due to the effects of contouring was not apparent.

A similar kind of task, that is, to find a fixed target after considerable pre-briefing, was conducted using television as the sensor and oblique aerial photographs for the basic scenes. In this case, the observers were briefed using vertical aerial photographs and maps, whereas the test trials simulated a sensor mounted on a vehicle closing on a target in a shallow glide. The trial scenes therefore, were oblique aerials. This change in viewpoint between briefing and test requires a considerable transformation on the part of the observer and places heavier demands on the quality of the test image. Representative results are shown in Figure 2-15 and it

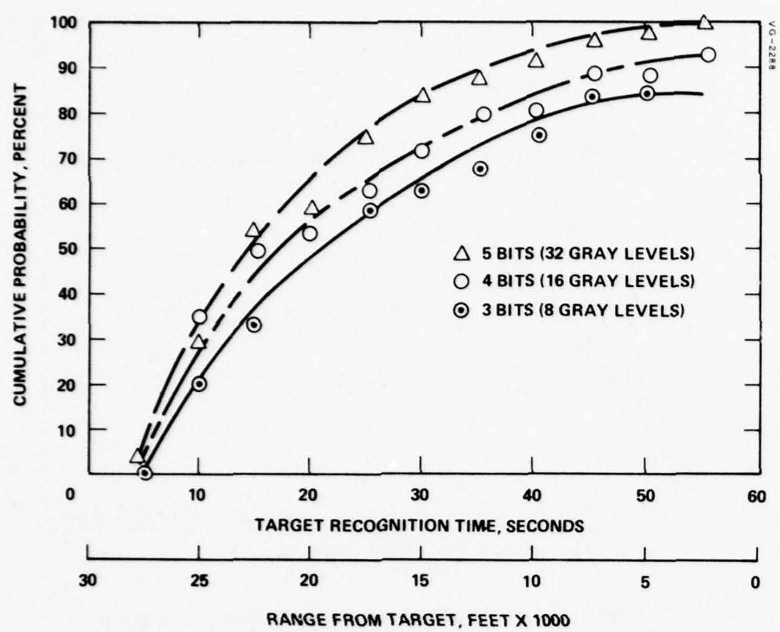

Figure 2-15. Effect of gray level quantization when the operator uses television to find a well briefed target.

can be seen that performance improves regularly from 3 to 4 to 5 bits.

The most severe task that we have used to assess the effects of gray scale quantization is the recognition task. For the operator this is a completely different task than finding a ground target on a radar display or finding a fixed target by contextual cues. The true recognition task depends not so much on the gestalt of the contextual information as on his ability to extract a shape signature from the displayed image which may, in turn, require the discrimination of small modulations within the target. The recognition task therefore is much more sensitive to variations in quantized video. Typically, the operator is required to name correctly a small vehicular target of the type shown in Figure 2-16. At the start of a trial, the target is circled — so that no search is required. The operator increases the target size with a zoom control until he can name it correctly. The size is then recorded. Typical results are shown in Figure 2-17, and they clearly show improved performance with increased gray scale bits.

The results of these performance studies, demonstrate the dependence of display design criteria on the task of the operator. The results from the radar study indicate that when the operator is thoroughly briefed, is looking for a target whose coordinates are known, and uses landmarks and contextual cues to find the target, the resolution and grey scale rendition of the display can vary over a wide range without having a major effect on radar target recognition performance. A small difference occurs when the gray scale quantization falls below 3 bits.

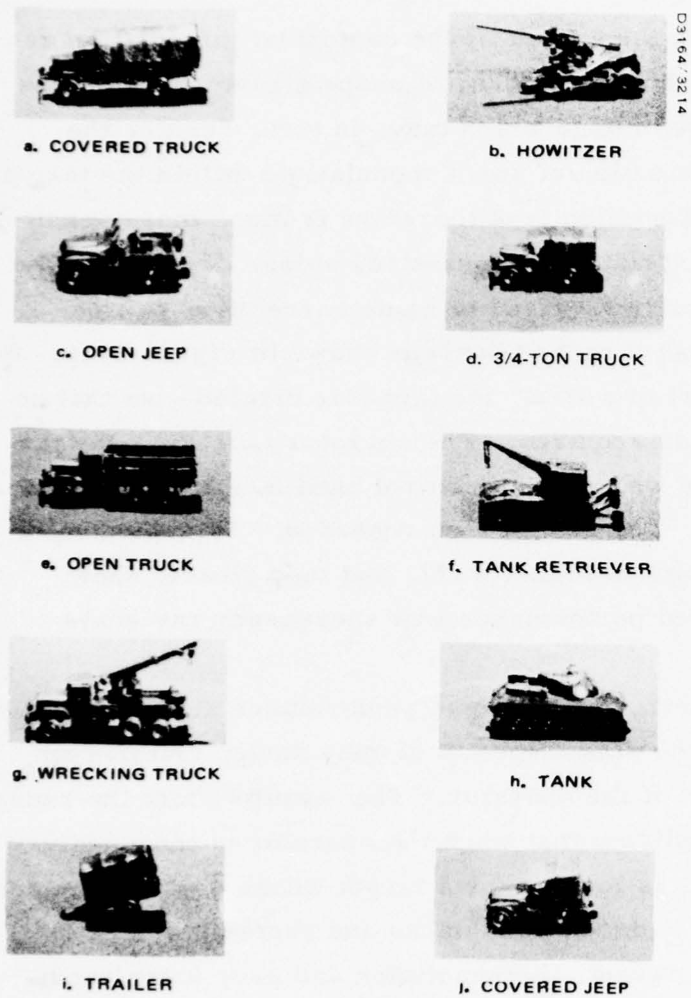

Figure 2-16. Kinds of targets used in recognition experiments.

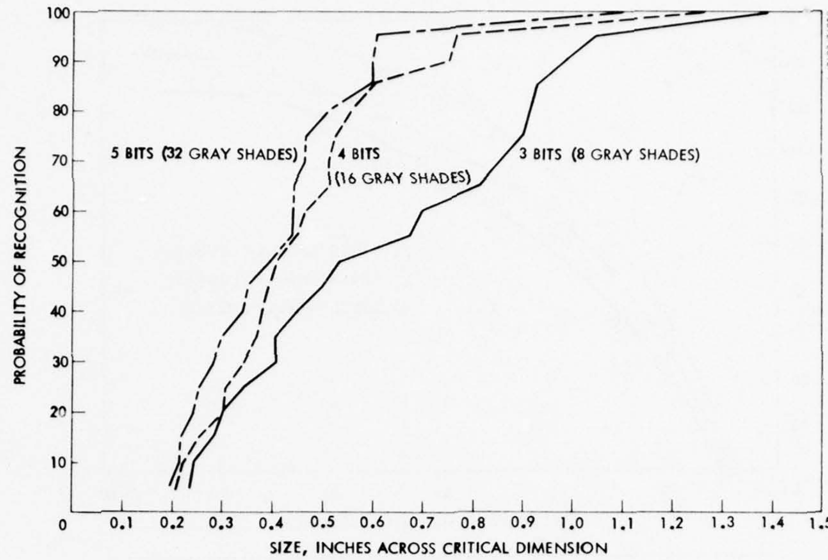

Figure 2-17. Effect of gray level quantization when the operator has to recognize the target by its shape signature.

Exactly the contrary is the case when the operator must recognize a target by its silhouette and small modulation differences within the target. Recognition performance when using electro-optical sensors against small tactical targets takes a sharp dip when the number of gray levels fall below 16 (4 bits).

Gaven, Tavitian, and Harabedian (1970) in a study of gray level encoding had observers identify vehicles from a scanned photograph of an array of vehicles positioned on a uniform background. They varied the

number of scans per vehicle (definition) and the number of bits used for gray scale. A sample of their data is illustrated in Figure 2-18.

Gaven, et al, conclude that there is a rapid increase in information from 1 to 3 bits but little if any

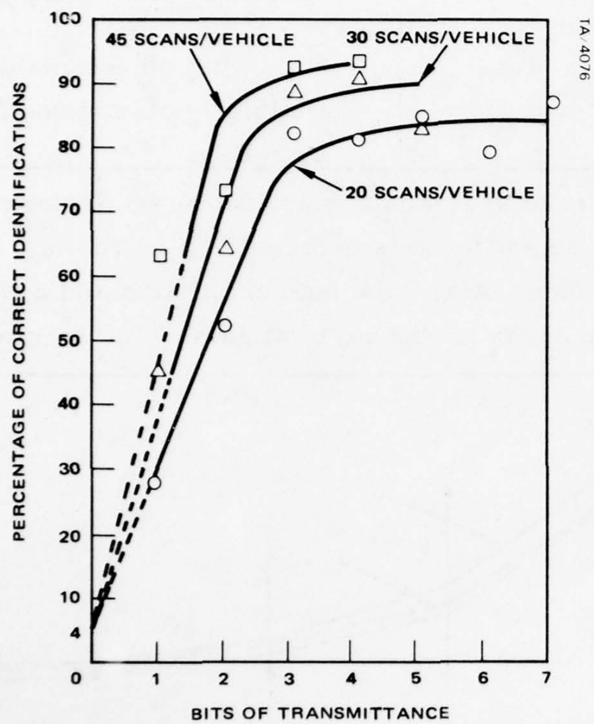

Figure 2-18. Identification performance with sampled images.

increase above 3 bits. Gaven's targets were overhead photographs of vehicles positioned on a plain background; there was therefore, no clutter. Considering the difference among tasks and imagery between Gaven's study and the previously described study, the data are felt to be in reasonable agreement.

While the previously cited works used some measure of performance to assess the effects of gray level encoding, there is an accompanying series of studies that used more subjective techniques to assess those effects. Bartleson and Witzel (1967) prepared a series of photographic prints of pictorial scenes and quantized the gray scale to 1, 2, 3, 4, and 5 bits and used as a reference a standard print of continuous tone. Twenty-five observers were individually asked to estimate how much intelligence they "could gather" about the original scene from the quantized print in question. The results are summarized in Figure 2-19 and show that there are big gains from 1 to 3 bits, but from then on an increase in the number of luminance levels (bits) yields increasingly less intelligence.

In conjunction with studies of pulse code modulation (PCM), Goldberg (1973) had experienced engineers estimate the effects of gray level encoding – among other variables – on the impairment of standard

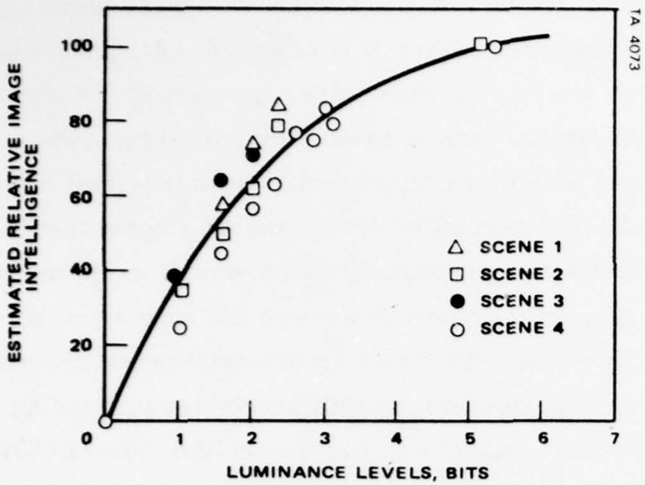

Figure 2-19. Estimated relative image intelligence conveyed by prints as a function of the number of luminance levels they contained (expressed in binary luminance bits)

television images. Using the European Broadcasting Union Impairment Scale, see Table II-3, the jurors rated each condition as compared to the standard. Representative results are depicted in Figure 2-20. The data demonstrate and the author concludes that encoding gray scale with 6 - 7 - or 8 bits is almost equivalent to continuous tone.

Considering the difference among observer tasks and experimental techniques, there is a remarkable consensus among these results. At some small risk, one may therefore hazard an overall estimate of the effects of gray scale quantization on performance. Such an estimate is depicted in Figure 2-21 with luminance bits on the horizontal axis and a figure of merit index on the vertical axis. The function is a

Table II-3. The European Broadcasting Union Impairment Scale.

Grade	Degree of Impairment
1	Imperceptible
2	Just perceptible
3	Definitely perceptible but not disturbing
4	Somewhat objectionable
5	Definitely objectionable
6	Unusable

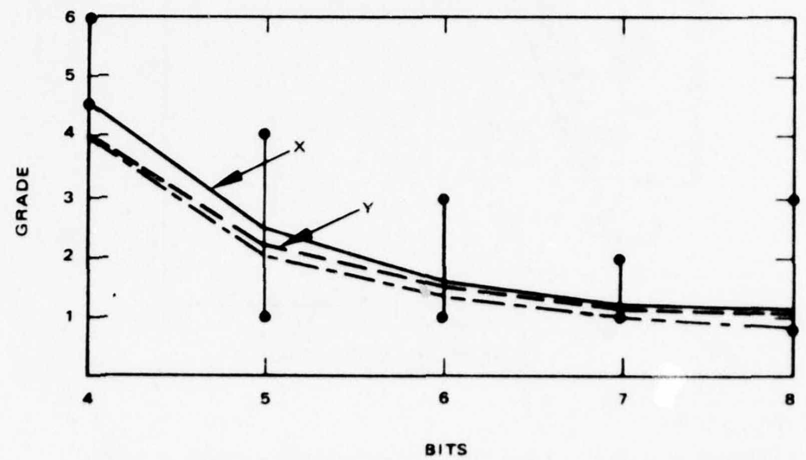

Figure 2-20. Encode $3f_{sc}$ (burst), no dither.

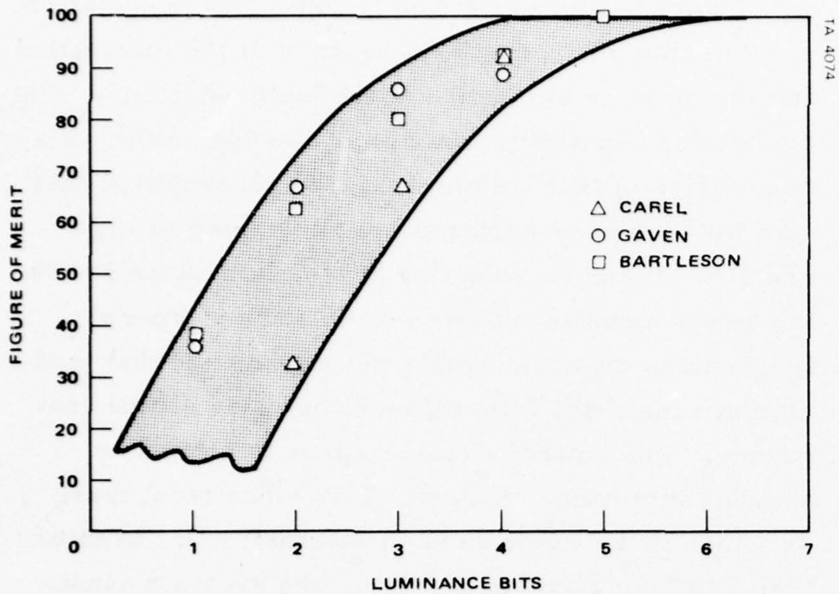

Figure 2-21. Region of useful gray scale bits.

little too severe for radar displays and a little lenient for high resolution electro-optical displays. For multipurpose monitors that may be used for all sensors, the curve appears to be about right.

2.4 SPATIAL FREQUENCY OF SENSOR INFORMATION

For a long time, there has been a controversy about the correct display size for displaying sensor data in tactical aircraft. There are conflicting criteria that make the choice anything but straightforward. In tactical aircraft, the limitations of cockpit space drives the selection towards the smallest possible display. The increased capacity of ground mapping sensors, particularly infrared systems, dictate that the display must become larger if the data mapped by the sensor are to be utilized by the crew. The issue has been exacerbated in the last few years by the advent of both radar and infrared sensors with up to 1000 line resolution; that is, sensors capable of resolving 1000 lines across one axis of their search pattern. At 30 inches viewing distance, a man can at most resolve on the order of 150 TV lines per inch. The ability of the eye to resolve 150 lines per inch holds, *however, only for extremely high contrast objects* and high visual adaptation levels. It is generally the case that targets of interest to the crew are not highly modulated but are of relatively low contrast.

Display size is not perhaps the proper characteristic by which to describe a monitor if one is, as we are, deriving design criteria in part from the properties of the observer. It was stated in the previous sections that a display cannot be comprehended in a single glance unless it is exceedingly small. Therefore, most displays are visually scanned by a series of fixations chained together by saccades; i.e., rapid eye movements from point to point. During the saccades nothing is seen. The

information displayed is perceived during the dwell time of the fixation and only in the sharp cone of vision around the fixation line-of-sight. The size of that cone is arguable and we arbitrarily have chosen it to be 4° in diameter. Peripheral vision while not sharp enough to extract fine grain data, may serve to cue the visual system where to look next and so determine the pattern of fixations. We may reasonably conclude that the most detailed target information is extracted in the region of the current fixation and that the quality of the image in that local region is the property related to observer performance.

One contribution to that quality is the number of sensor lines of information displayed per degree of visual angle subtended. This paradigm allows us to treat local image quality (discernible information lines per degreee) as a generalized characteristic related to the probability of target recognition whereas display size (area) is a characteristic properly related to acquisition time in cases where the display must be searched.

The question of the proper number of information lines per degree of visual angle can once again be addressed initially from a consideration of the visual modulation sensitivity function.

The sensitivity of vision to luminance modulation is a function of the spatial frequency of the modulation and the average luminance of the pictured scene. The modulation sensitivity function of the eye, MSF, is a description of that relationship. Representative MSF data for sine wave patterns are illustrated in Figure 2-8. It can be seen that at high luminance levels the eye is most sensitive to modulation at spatial frequencies around 6 cycles per degree and that modulation sensitivity falls off on either side of that frequency. The entire response curve is shifted as average luminance changes. It is clear from these data that at the luminances of interest; i.e., greater than 50 fL for daylight displays, the greatest sensitivity of the eye is in the region of 5 cycles per degree. This implies that if one wants to be able to discriminate extremely low modulations, those modulations should appear on the display at frequencies on the order of 5 cycles per degree. (A degree is about 0.5 inches at 30 inch viewing distance and 5 cycles per degree translates into 20 TV lines per inch.)

A common criterion for recognition is that 8 to 10 discriminable information lines be laid across the minimum axis of the target for a recognition probability of 50 percent. The key word is "discriminable", for simply to have the target defined by lines in the

geometric sense is not adequate. The MSF data demonstrate that discrimination is most sensitive when the spatial frequencies are on the order of 5 cycles per degree. A little calculation quickly shows that displays on which sensor resolution is mapped to a display at a visual spatial frequency of 5 cycles are very large indeed. For example a television sensor system with a resolution of 500 TV lines (250 cycles) would, to meet this criterion, require a display width of about 25 inches if viewed at 30 inches. Such display sizes are unreasonable for tactical aircraft. It is equally unreasonable, however, to keep increasing the capacity of the sensors and expect that the increased capacity can be operationally useful if the display sizes are restricted to 4 to 6 inches at most. On the basis of this brief analysis, one expects that a penalty is being paid by use of small displays.

It is of course not necessary that all of the sensed data be mapped to the display. While in "straight-through" display systems (as conventional television), there is a one-to-one correspondence between what the sensor is scanning and what is displayed, modern processing and scan conversion techniques would permit displaying only a portion of the sensed data if that were advantageous.

The central issue is suggested by the analysis based on the MSF data: what is the optimum spatial frequency with which sensor data should be mapped to a display if the utmost visual sensitivity is required. A small study was conducted at Hughes to develop empirical data which demonstrate the relationship between target recognition performance and the displayed spatial frequency of the sensor data.

The task for the operator was chosen carefully. It is generally the case that variations in display characteristics have little effect on performance when the task of the operator depends to a large extent on finding a stationary fixed target by use of contextual cues. Those contextual cues are used so intelligently that the target can be found in spite of large variations in display size, resolution, and grey scale rendition. We have found in our laboratories that the effects on operator performance of variation in display characteristics are most sensitively measured with a target recognition task. This task typically requires the operator to discriminate among small tactical targets: tanks, jeeps, trucks, and the like. The recognition task demands the visual discrimination not only of the contrast of the target to its background but small modulations within the target — precisely

the kinds of marginal modulations that may be subthreshold in displays that are inadequately sized or in which the sensor data has been mapped to the display at an inappropriate spatial frequency.

Such a test was employed in this study. In this particular experiment the modulation of tne target with the background was varied by use of a masking luminance. The observor was required to identify vehicle targets (tanks, jeeps, etc.) all of which were defined by 32 scan lines (16 cycles) per target height. The targets were viewed at distances corresponding to 2.5, 4.0, 8.0, 16.0, and 32.0 cycles per degree and the modulation varied until the target was correctly identified. A more complete description of the procedure may be found in Carel, Hershberger, and Herman (1976).

The cumulative percent correct recognitions are plotted as a function of modulation at recognition in Figure 2-22. Examination of these data clearly shows best performance for the 4 and 8 cycle conditions, worst performance for the 24 cycle conditions, and performance for the 2.5 and 16 cycle conditions somewhere in the middle. Median scores for these conditions demonstrate the same phenomenon. The medians taken across subjects and targets are contained in Table II-4.

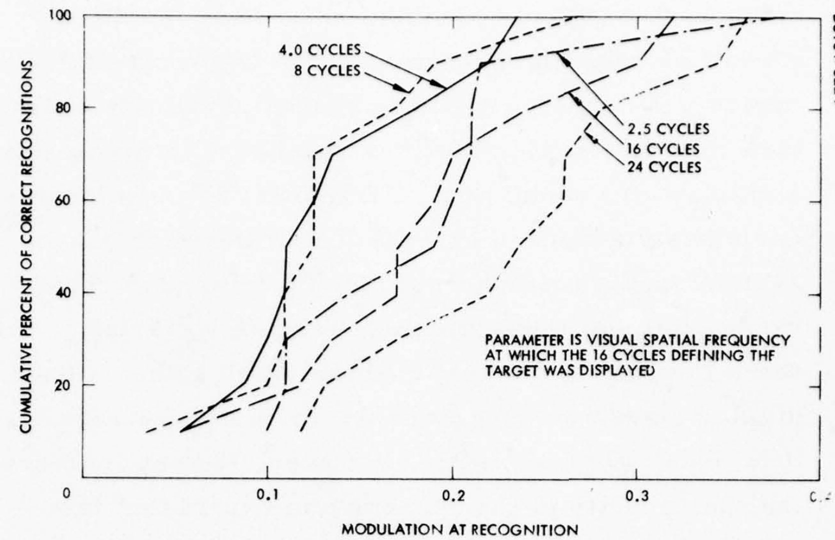

Figure 2-22. Cumulative percent of targets recognized as a function of visual spatial frequency and modulation.

Table II-4. Modulation at 50% Recognition

	Visual Cycles Per Degree				
	2.5	4.0	8.0	16.0	24.0
Modulation	0.20	0.12	0.13	0.18	0.25

An analysis of variance was conducted on the modulation scores with the results shown in Table II-7. Spatial frequencies, observers, and targets were all highly significant; that is, the odds that the results could have occurred by chance are less than 1 in 1000. Of equal interest are the values of ETA^2: the percent of the variance contributed by a variable. Spatial frequency accounted for 23 percent of the study variance – a large proportion for studies of this kind where such effects are typically small.

Table II-7. Analysis of variance: modulation scores

Source	SS	df	MS	F	P	Percent Eta^2
Observers	1022.344	4	255.586	14.32	0.001	32
Spatial Frequencies	740.814	4	185.2035	10.38	0.001	23
Targets	868.984	9	96.554	5.41	0.001	27
Residual	571.044	32	17.845			18
Total	3203.186	49				

The results confirm the hypothesis based on the visual MSF that best performance in a critical recognition task would be found when the spatial frequency of the displayed information is on the order of 5 to 6 cycles per degree. There is a fall-off in performance below 4 cycles and above 8 cycles.

Because of equipment limitations, this study was conducted at luminance levels averaging 0.1 fL. This level is appropriate for nighttime display luminance. One may hypothesize that a similar function would occur at higher daytime luminances and that, at a first approximation, the performance curves for target recognition would be displaced downward in modulation with increasing luminance by the same ratio as are the MSF curves. The MSF curves also shift the spatial frequency of maximum sensitivity to higher spatial frequencies as luminance rises. Extrapolated curves for target recognition have been constructed following this reasoning and are shown in Figure 2-23.

Some speculative implications may be drawn from these data. The first of these deals with optimum

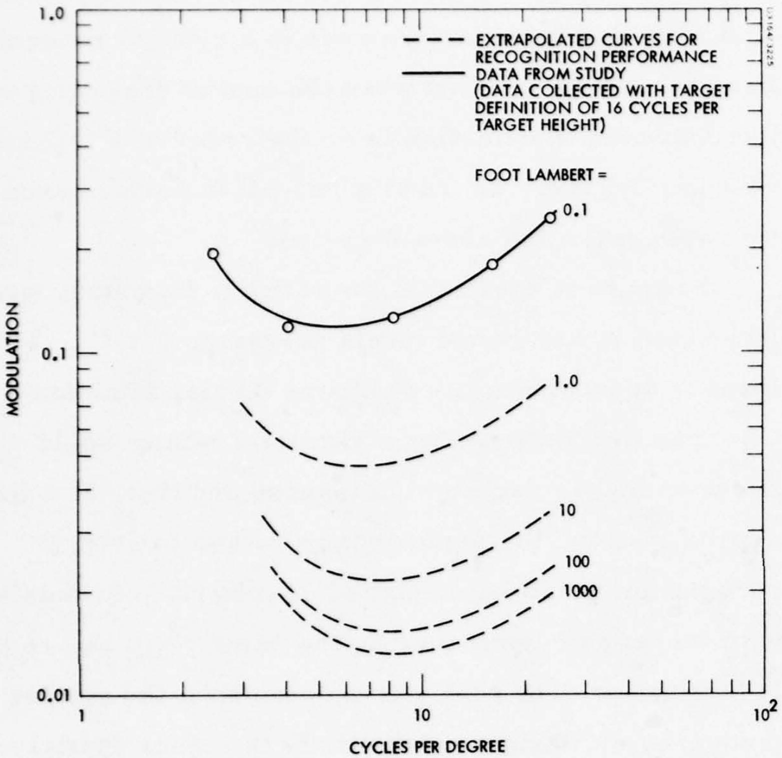

Figure 2-23. Recognition performance curves for different luminance levels.

display size. In straight-through display systems as, for example, a television sensor display sensor where the display follows in synchrony with the sensor and where the entire output of the sensor is mapped to the display, a figure-of-merit for display size may be estimated for the case where the operator task is similar to the demanding task used in these experiments. As the conclusion with regard to display size is a hypothesis that needs further confirmation, we shall make the point with a single example. Assume a 525-line television sensor display system with 480-active display lines. Using the modulation sensitivity curves illustrated in Figure 2-23, a figure-of-merit for display size (height) has been calculated as a function of viewing distance for a representative daylight ambient as shown in Figure 2-24. At a viewing distance of 30 inches – the restrained pilot viewing distance – the optimum display size is on the order of 13 to 16 inches. The effectiveness of the display falls off as it gets larger and smaller. For these conditions, a 6-inch display is about 75 percent as effective as a 14-inch display. At a viewing distance of 15 inches – perhaps achievable if the pilot leans forward – the optimum size is on the order of 6 to 8 inches. At this shorter distance, a 4-inch display (characteristic of current proposed display sizes) is about 88 percent as effective as the optimum. The optima for sensor displays will be shifted to the right, that is, the display must be

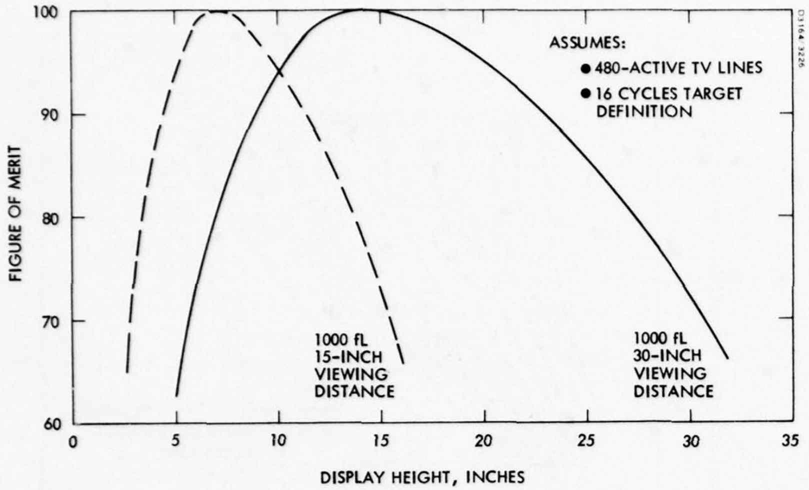

Figure 2-24. Figure of merit for display size for two viewing distances (daylight).

larger, when they are operated in the dim conditions of twilight and night.

It should be noted that these curves for optimum display size are applicable only when the utmost is required of the sensor-display-operator system, that is, when the target is low contrast and when the operator is required to recognize the target on the grounds of its internal modulations and contrast with the background. Other studies have repeatedly demonstrated that operator performance is insensitive to variations in display size when the task is to find and recognize targets and landmarks by contextual cues or the target has a high contrast with the background.

The second equally speculative implication – carried with the same caveats – deals with the issue of the visual spatial frequency with which sensor data should be mapped to the display. Should, for example, 500 resolution elements of sensor data be displayed at visual spatial frequencies of 20, 40, or 80 resolution elements per degree of visual angle? With modern processing systems it is not necessary that the display replicate all the information provided by the sensor. Sensed information can be stored and all or part of it called up for display. This permits considerable flexibility in display and allows one to separate out the quality of the display – its flicker, its raster structure, etc. – from the spatial and temporal granularity of the sensor input. One can imagine a high quality flicker free display with small spot size and closely packed, merged raster on which the sensor data are reproduced at a much coarser resolution than the display is capable. This would be done in the interest of taking

advantage of the visual response of the operator whose maximum modulation sensitivity lies in the region of 6 to 8 cycles per degree. Thus the display medium might have a resolution of 160-TV lines per inch (40 cycles per degree at 30 inches) but the sensed resolution data be mapped at a visual spatial frequency of 32 resolution elements per inch (8 cycles per degree at 30 inches) in order to take advantage of this region of operator sensitivity.

We have used the data from the present study in conjunction with results of a previous study (Rogers and Carel, 1973) to calculate the performance impact of the visual spatial frequency with which sensed information is presented on the display. Figure 2-25 shows the relationships among definition (the number of sensor lines laid across the target), the displayed spatial frequency of the sensed resolution elements, and the probability of recognition. This set of curves says that if the sensor lays 20 line pairs (cycles) across the major axis of the target, then, if these 20 cycles are displayed at a visual spatial frequency of 10 cycles per degree, the probability of recognition will be about 90 percent; if they are displayed at 20 cycles per degree the probability of recognition will be 67 percent; and if they are displayed at 30 cycles the probability of recognition will be about 55 percent. Co... versely, as the graphed parameters are iso-probabili... curves, the same operator performance can be achieved by the graphed combinations of definition and display spatial frequency.

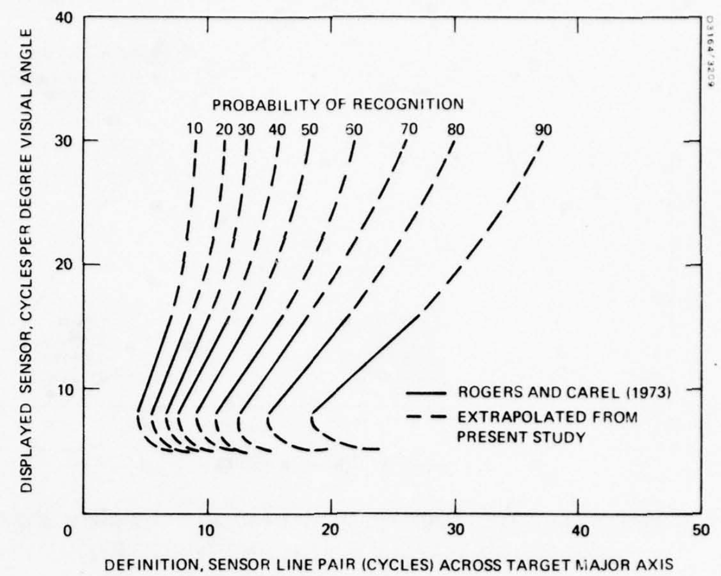

Figure 2-25. Probability of target recognition as a function of target definition and display spatial frequency.

3.0 TEMPORAL FACTORS IN IMAGING SENSOR DISPLAY DESIGN

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3.1 INTRODUCTION

Because visual perception is a process that occurs in time, temporal aspects of both the input and the visual system with processing can affect what is ultimately perceived, which in turn will affect task performance. The temporal properties of the visual system interact with incoming temporal and spatial information to produce an apparently continuous and stable representation of the world. Two major aspects of a sensor display may vary with time: change in luminance over time or change in spatial position of some target over time. In sensor displays, a series of stationary stimuli are briefly presented to the operator, rapidly fade, and are regenerated. Between each successive regeneration, stimuli may be spatially displayed (i.e. new information will be presented) or the identical stimuli may be represented. The rate at which stimuli are regenerated will be referred to as the refresh rate of the display, while the rate at which new information is provided will be termed the update rate.

The refresh rate can be combined with the effects of other variables to produce a flicker-free display; such a display takes advantage of the temporal limitations of the visual system to lead to the perception of a continuous, steady field of light. Similarly, the update rate is an important determinant of the perception of smooth, continuous motion from successive, discrete images, and again, it is the limited temporal discrimination of the visual system that produces this perception. These two variables do not work in isolation, but depend on a considerable number of other external factors, as well as the state of the visual system itself. These variables and their interactions will be discussed in relation to the quality of the display and its effect on task performance.

3.2 CRITICAL FLICKER FREQUENCY: PSYCHOPHYSICAL STUDIES

When a periodic stimulus is repeated at a fast enough rate, it will appear fused to the observer. The

refresh rate necessary for fusion to occur is the critical fusion frequency (CFF), and once this threshold has been reached, further increases in frequency have no effect visually or on performance (Crook, Bishop, Fehrer, & Wade, 1960). At moderate intensities, displays driven by AC power will appear continuous and identical to displays driven by DC (Brown, 1965), and will match in brightness a steady light with the same time-average luminance. This relationship is given by the Talbot-Plateu law:

$$L_m = 1/t \int_o^t L\,dt$$

where L_m is the luminance of the steady light, L is the instantaneous luminance of the time varying field, and t is the period of a single cycle of the varying field. It should be noted that this relationship may not hold under high intensities (Grunbaum, 1898) or when the periodic stimulus is presented to the peripheral portion of the visual field (Le Grand and Geblewicz, 1937).

Below the CFF, the visual field will be seen as flickering. Flicker may be simply annoying or distracting to the operator, or may totally incapacitate him (Berry and Eastwood, 1960). Headaches, flicker vertigo and epileptic seizures are commonly reported reactions to flicker, with the most disturbing frequencies ranging from 2-16 Hz (Brazier, 1954). These reactions will reduce the level of performance at any task, but flicker particularly degrades perceptual-motor coordination. Aislieger and Dick, (1966) examined the effect of a 5-Hz flashing light on a button-pushing reaction time task, a short-term memory (digit span) task, a perceptual-motor (pursuit rotor) task, and a complex task that involved all three of the simple tasks. Performance was only degraded on the perceptual-motor task, with subjects lagging behind the target in their tracking and reporting that the target appeared to be moving faster when the light was flickering. However, there are wide individual differences in the nature of the effects and the extent to which flicker is perceptible or annoying.

The mechanism by which fusion occurs is not known. It is known that the receptor cells in the retina respond to frequencies up to at least 40 Hz (White, Cheatham and Armington, 1953) with some estimates as high as several hundred Hz. However, the cortical response, which occurs 50 to 100 ms after the receptor output, peaks at a maximum of 8-10 Hz (Harter and White, 1967); light impulses must be spaced between 10 and more often 100 ms apart for cortical resolution (Haber

and Hershenson, 1973). The perception of flicker reflects the cortical response; regardless of the physical frequency, if any flicker is seen, subjects can at most report 8-10 flashes per second (Cheatham and White, 1952; Forsythe and Chapanis, 1958).

Temporal information is therefore lost between the receptor and the cortex; it appears as if a discrete sampling process occurs after the receptor output. While there is little physiological evidence to support it, a heuristically valuable conception of this sampling process has been put forth by Stroud (1956). He suggests that time is quantized into perceptual moments, or time frames about 100 ms in length. Any events falling within this time period cannot be temporally discriminated, although they may be distinguished from other criteria such as location or size. Such events will be seen as occurring simultaneously, and for these events Bloch's law (Intensity · Time = Constant) will hold, at least under scotopic conditions. It has been empirically determined that the critical duration for Bloch's law is in fact 100 ms for vision; for photopic vision, events must occur within a period of about 20 ms in order to be integrated. Such a variable time frame, about 100 ms for scotopic vision and perhaps as short as 10 or 20 ms for photopic illumination would be a useful extension of the Stroud theory. Pieron (1952) suggests that the visual system may be conceived as sampling a series of snapshots, each of which would correspond to a time frame in the Stroud conceptualization. A sampling process such as this is useful in explaining why an intermittent light may appear identical to a continuous one, as well as why successive, spatially displayed images will appear identical to actual motion. If the visual system converts continuous stimulation into intermittent, discrete images and subsequently integrates or fuses them at some more central location, then at certain presentation rates, intermittent stimuli may also be fused or integrated. The perception of continuous and intermittent stimulation would then be expected to be identical.

3.3 LUMINANCE

The Stroud conception may provide some explanation for fusion and other temporal phenomenon of the visual system, including apparent motion. For example, the CFF increases linearly with log luminance (Hecht and Shlaer, 1936). This relationship is shown in Figure 3-1 for seven wavelengths matched for photopic brightness. The branching curves in the scotopic region which reflect brightness differences perceived by rods, and are artifacts of the matching procedure. In genal, the CFF luminance relationship holds independent of wavelength, and is given by the Ferry-Porter law:

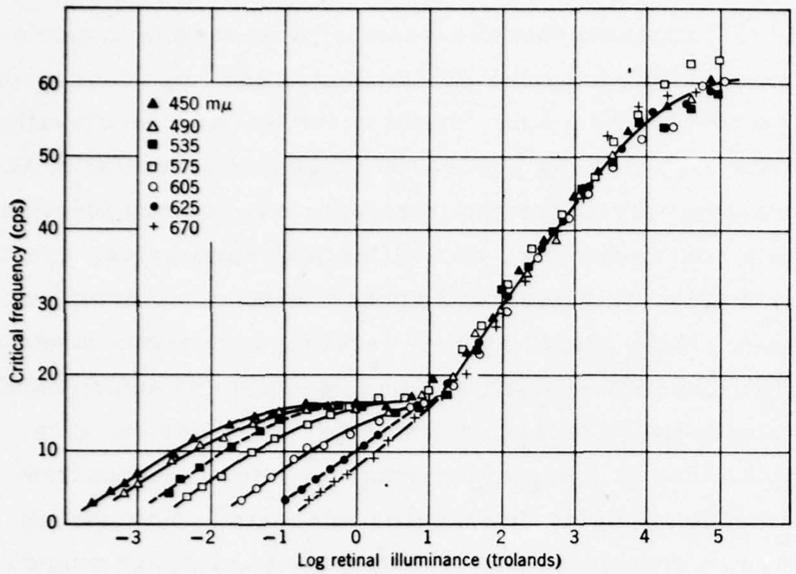


Figure 3-1. Relationship of CFF to log retinal illuminance for seven spectral regions (Hecht and Shlaer, 1936).

CFF = a log L + b. The value of a has been estimated to be between 10 and 15 for daylight vision and 1 and 2 for night vision.

According to the perceptual moment hypothesis, fusion occurs when the pulse rate is greater than the time frame; the rise in CFF would be explained by a shorter time frame that occurs as light adaptation increases at higher luminance levels. However, for long trains of pulses that span several time frames, complete fusion over time is not explained by this hypothesis. If, however, sampling occurs at a rate different than the time frame duration, then the conception is valid for these cases.

A more useful method of examining the relationship between luminance and CFF takes into account the modulation amplitude. Luminance may be varied sinusoidally about a mean level up to amplitudes of 100 percent; amplitudes greater than 100 percent, while physically impossible, may in fact be obtained with square waves. A square wave composed of a fundamental sinusoidal wave and harmonics may be flashed on and off to give a physical modulation amplitude of 100 percent; however, the amplitude of the fundamental is 1.27 times the amplitude of the square wave, leading to a modulation amplitude for the fundamental of 127 percent. There is considerable evidence that in general, the visual system responds to the fundamental sinusoid both in frequency below 15-20 Hz (Ives, 1922a) and amplitude (Gibbons and Howarth, 1961).

The relationship between retinal illuminance, frequency, modulation amplitude, and CFF is shown in Figure 3-2 (Kelly, 1961b) which indicates that the Ferry-Porter Law only holds over a limited range of adaptation levels (retinal illuminance), and at very small modulation amplitudes, two CFF values may be found for a given adaptation level.

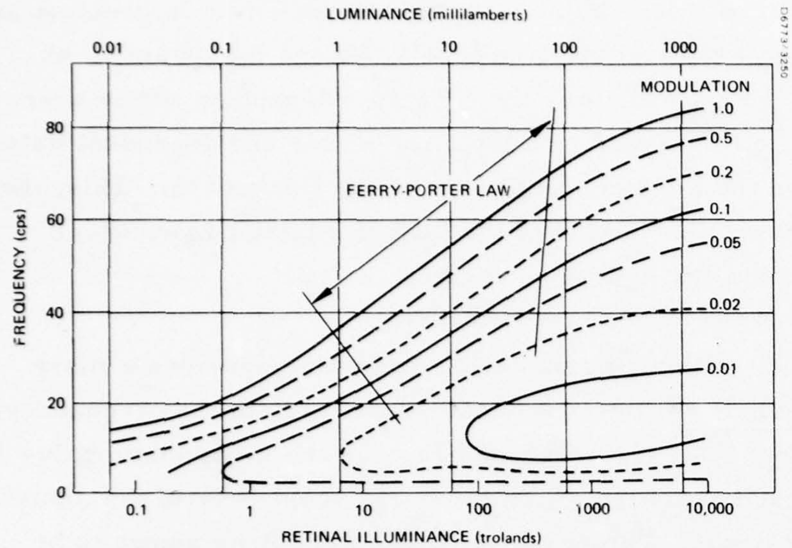


Figure 3-2. Threshold frequency vs adaptation level as a function of modulation (Kelly, 1961).

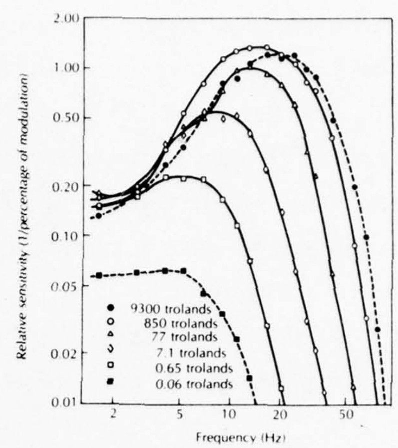


Figure 3-3. Threshold sensitivity to percentage of modulation at various luminance levels and frequencies (from Kelly, 1961).

The amplitude sensitivity of the visual system is useful in explaining and predicting CFF. Using an edgeless field to eliminate spatio-temporal interactions, Kelly determined typical relative and absolute amplitude sensitivity curves plotted versus frequency at several levels of adaptation.

Figure 3-3 illustrates the sensitivity to percentage of modulation (the ratio of modulation amplitude to the average level). The coincident curves at low frequencies are examples of Weber's Law:

$$\Delta I/I = k;$$

low frequency modulations just at threshold will pass the CFF as the average luminance level is increased, but the modulation will again be apparent when its amplitude is increased until the modulation percentage is the same as at the original threshold level.

In general, Figure 3-3 illustrates that amplitude sensitivity just rises to a maximum as frequency increases up to about 10-30 Hz; at frequencies above

this, relative amplitude sensitivity rapidly decreases. Bandwidth of the visual system also increases with adaptation level, so that the CFF remains at about 4.5 times the frequency of maximum sensitivity at all adaptation levels except 0.06 troland. In addition, the relative amplitude sensitivity increases with light adaptation except at low frequencies.

In Figure 3-4, the same data is plotted as a function of absolute amplitude. It may be seen from this curve that absolute amplitude sensitivity is greatest at the lowest adaptation levels. More importantly, at high frequencies, the CFF is independent of the average luminance or adaptation level, and dependent only on the absolute amplitude of the fluctuation. This, then, is an illustration of the Talbot Plateau Law, which holds for high frequencies.

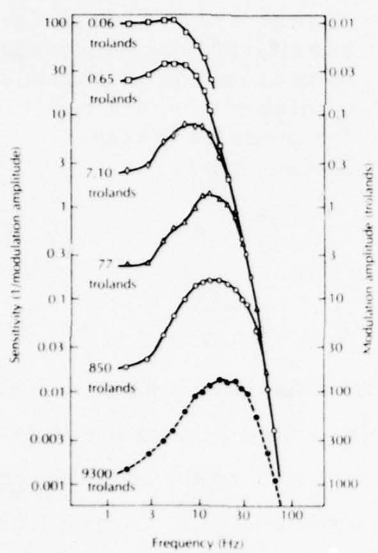


Figure 3-4. Threshold sensitivity to modulation amplitude at various illumination levels and frequencies (Kelly, 1961).

3.4 SPATIAL VARIATIONS

Although modulation amplitude provides a more precise reflection of the visual system than frequency, the CFF has nevertheless been the more commonly-used measure of the temporal sensitivity of the visual system. Temporal sensitivity has been shown to be affected by a number of other factors both singularly and in combinations; the design engineer should be aware of these factors when predicting the CFF.

3.4.1 Target Area

Spatial variations in the stimulus will affect the value of the CFF; in general, the log area of the target is linearly related to the CFF over a large luminance range and for stimulation well beyond the foveal region (Berger, 1953; Roehrig, 1959a). Granit and Harper (1930) first investigated this relationship and provided the formulation

$$CFF = c \log A + d$$

where A is the stimulus area, and c and d are constants. However, this relationship does not hold under all conditions, and interacts with retinal illuminance (adaptation level).

For example, Hecht and Smith (1936) have demonstrated that as stimulus area increases, the CFF - log luminance relationship shifts to higher values, and at low luminance levels, a departure from the linear relationship is found when target area is large. These relationships are illustrated in Figure 3-5.

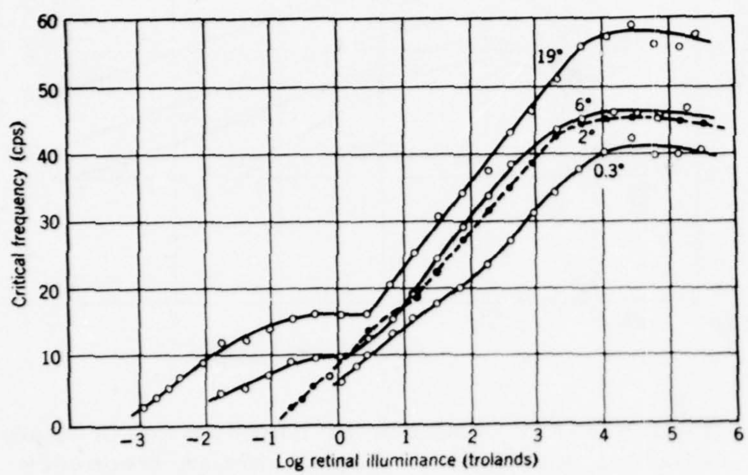


Figure 3-5. Influence of area of centrally fixated test field on relation between critical frequency and logic retinal illuminance (Hecht and Smith, 1936).

3.4.2 Retinal Locus of Stimulation

The low luminance branches in Figure 3-5 are associated with rod functioning, and only occur with larger targets that stimulate the peripheral portion of the retina. The retinal location by luminance interaction is shown in Figure 3-6 for a test area of 2^{o} on a 10^{o} surround (Hecht and Verrijp, 1933a). It may be seen that at high adaptation levels, the eye is more

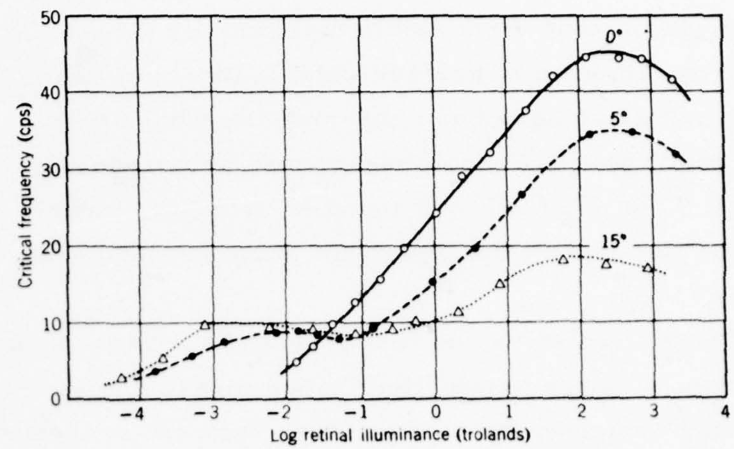


Figure 3-6. Relation between critical frequency and log retinal illumination for white light for three different retinal locations at the fovea and at 5^{o} and 15^{o} above the fovea (Hecht and Verrijp, 1933).

sensitive to temporal variation in the fovea, but at low illuminance levels, the peripheral region of the retina yields the greatest sensitivity. This relationship is further complicated by an interaction with stimulus area; for very small test areas (less than 1°), sensitivity decreases with any displacement toward the periphery (Creed and Ruch, 1932), while with large test areas, peripheral sensitivity may be higher than foveal.

3.4.3 Surround Variables

The area and illumination of the surround may also be important variables in determining the CFF, and in the absence of any surround luminance, headaches and glare have been reported (Brown, 1965). With small test fields and background areas ranging from 0.5° to 4°, CFF was found to increase linearly with an increase in the logarithm of background area (Foley, 1961).

Berger (1954) varied test area and the ratio of the surround to flicker area illuminance measuring the resultant effect on the CFF. These data are presented in Figure 3-7.

Although the addition of an illuminated surround reduces discomfort, it will also raise the CFF somewhat for a foveally fixated target, with maximum sensitivity reached when the surround matches the

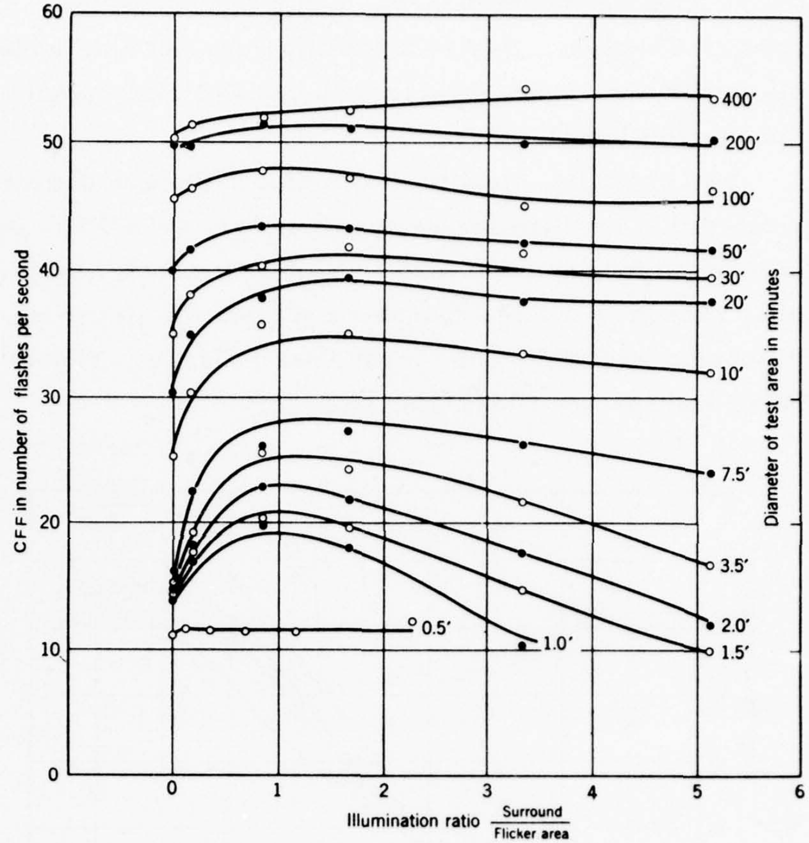


Figure 3-7. Influence of illumination of white adjacent surround on flicker fusion frequency (FFF) in the human fovea. Test-field diameters from 0.5 minute of arc 400 minutes of arc. Surround luminance varied between 0 and 5.2 times test-field luminance (0.27 millilambert). Each point is the average of 30 measurements (Berger, 1954).

average brightness of the test area. For peripheral targets, the maximum CFF is found when the surround brightness is lower than the test field (Lythgoe and Tansky, 1929).

The surround and target will interact to produce spatial edge effects, which in turn interact with the temporal factors of the visual system. A loss in resolution will raise low frequency flicker thresholds, but has no effect at high frequencies (Kelly, 1969) when measured by modulation amplitude.

3.4.4 Temporal Patterns of Stimulation

Another factor affecting the CFF is the temporal pattern of stimulation. Changes in the relative proportion of light and dark (light-time fraction) per cycle will interact with many of the variables previously discussed. One general trend that may be extracted from the literature, however, is that when average luminance is held constant, the CFF linearly increases with an increase in the logarithm of the dark portion of the interval (Pieron, 1961).

3.4.5 Other Variables

In addition to the many variables presented, the CFF varies considerably among individuals. Temporal sensitivity will decrease with age, increase with an increase in environmental temperature, and be affected by such short-term factors as body position, concentration and attention. These sensitivity differences, however, are not likely to significantly affect predicted CFF levels.

3.5 CRITICAL FLICKER FREQUENCY: APPLIED STUDIES

Much of the research presented was performed under highly artificial laboratory conditions which may not apply to actual display viewing conditions. For example, many of the studies use artificial pupils, scotopic adaptation, or edgeless, blurred stimuli; these conditions are unlikely to be encountered under typical viewing situations. In addition, these studies do not include variation in display factors such as phosphor persistence and its interactions with target size, average luminance, and bandwidth requirements of a system. However, a number of applied experiments have been performed which may provide more pertinent information for the design engineer.

Turnage (1966) conducted a series of studies to determine wide-field CFF values for CRT-human systems, and found that these CFF values for a stationary stimulus are considerably lower than those found in investigation of just the visual system. Seven phosphors (P1, P4, P7, P12, P20, P28 and P31) were employed to generate a 5/32 inch sharp-edged spot with a dim surround (3 fL), viewed at a distance of

12-15 inches (30-38 cm), for a target subtense of 36-44 arc minutes under ambient light of 10 ft candles (normal reading light). Targets were presented at 10, 32 and 100 fL average luminance levels, with either sine or pulse modulation. For the latter modulation, a pulse-duty cycle of 2 percent was employed. Curves of CFF versus modulation index (the ratio of the amplitude of the fundamental component to the average value) with sine modulation are presented in Figures 3-8 through 3-14.

These curves indicate a much lower sensitivity to flicker than the values obtained in laboratory conditions; this is for the most part due to phosphor persistence, which decreases the modulation index of applied excitation.

Particularly pertinent to sensor displays are the Turnage data on pulse modulation. The obtained CFF values are plotted versus brightness for each of the sensor phosphors in Figure 3-15.

The CFF values illustrated in Figure 3-15 are lower than those which should be expected with a display or more than a single stimulus due to higher average illumination. In addition, when ambient light is higher than the 10 foot-candle value used in these experiments, a lower CFF value than would be predicted from extrapolation of Figure 3-15 should be anticipated since the smaller resultant pupil will reduce the image brightness.

Both Turnage (1966) and Krupka and Fukui (1973) have employed phosphor persistence data in developing

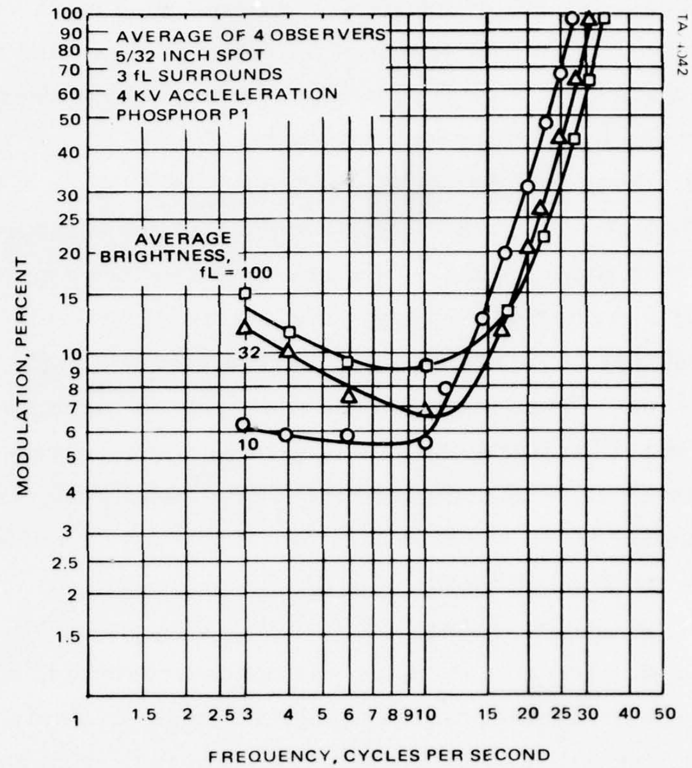


Figure 3-8. Sine modulation critical fusion frequency for phosphor P1 (Turnage, 1966).

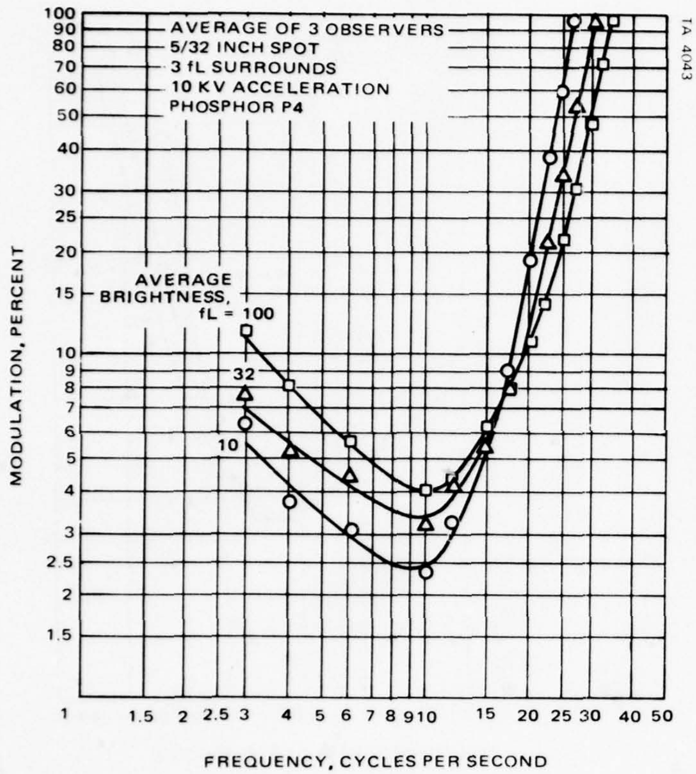


Figure 3-9. Sine modulation critical fusion frequency for phosphor P4 (Turnage, 1966).

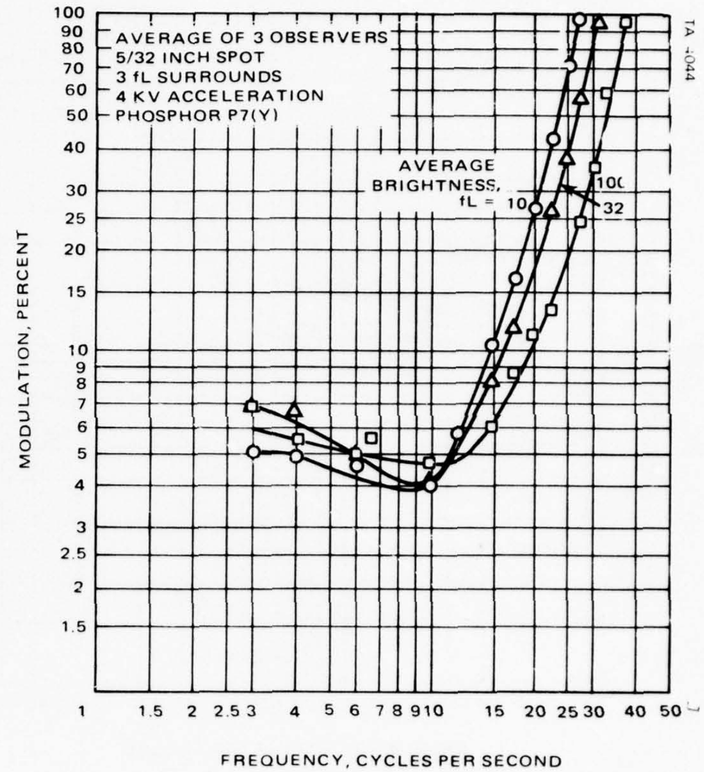


Figure 3-10. Sine modulation critical fusion frequency for phosphor P7 (Turnage, 1966).

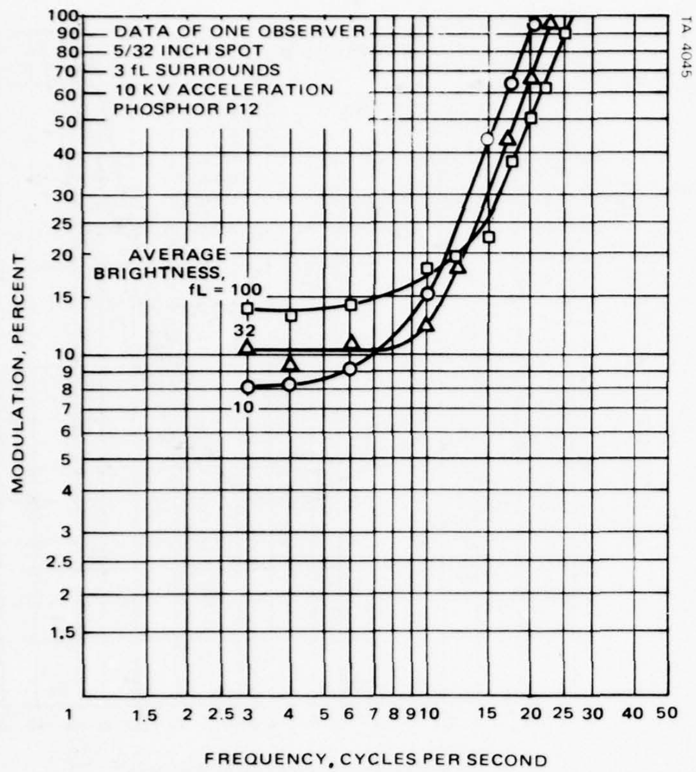


Figure 3-11. Sine modulation critical fusion frequency for phosphor P12 (Turnage, 1966).

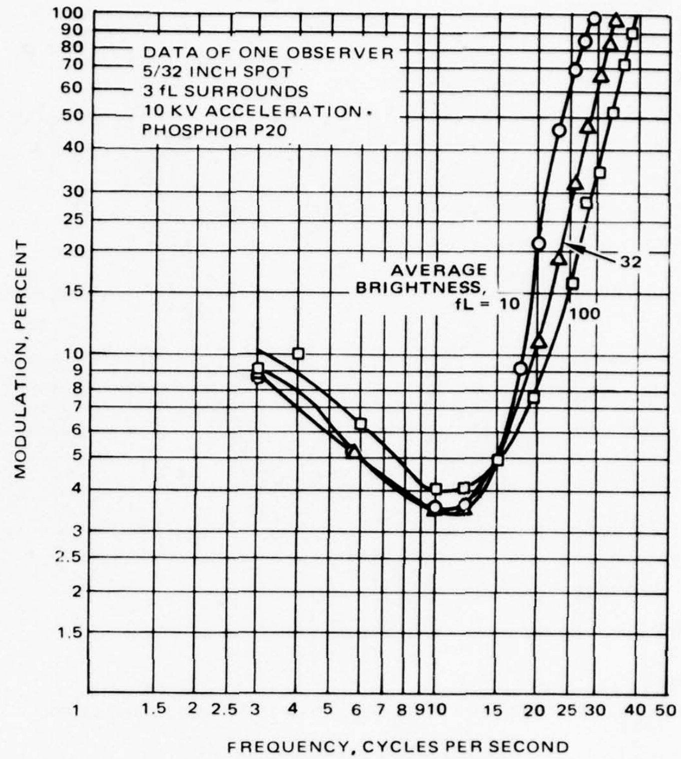


Figure 3-12. Sine modulation critical fusion frequency for phosphor P20 (Turnage, 1966)

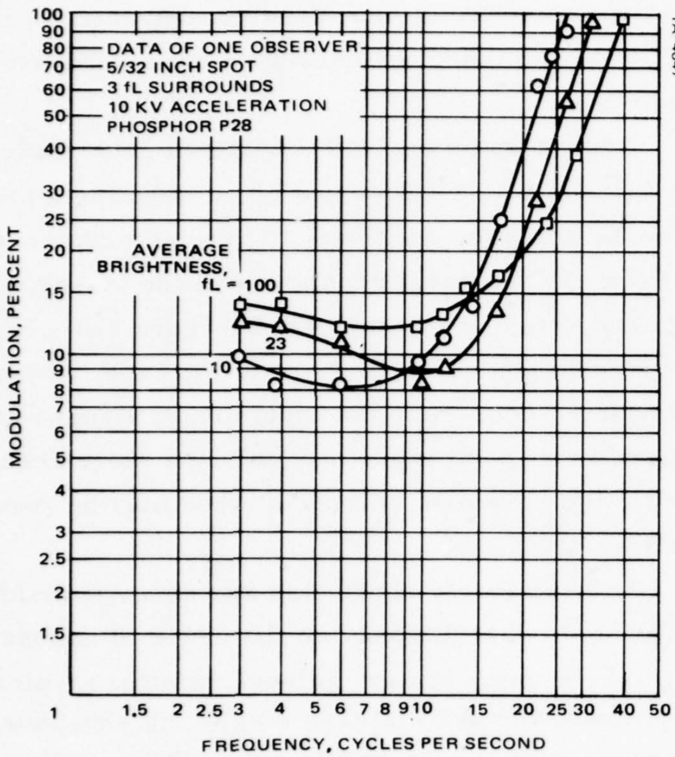


Figure 3-13. Sine modulation critical fusion frequency for phosphor P28.

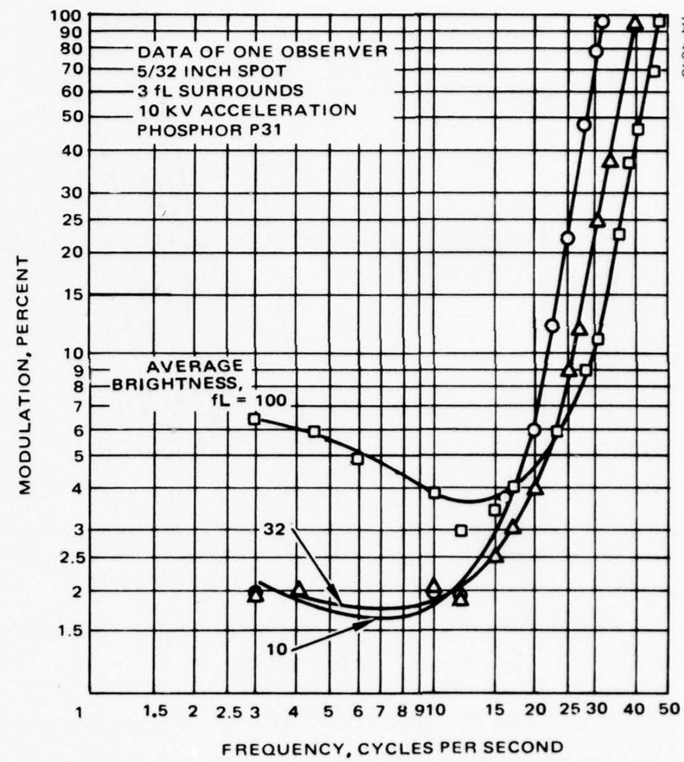


Figure 3-14. Sine modulation critical fusion frequency for phosphor P31.

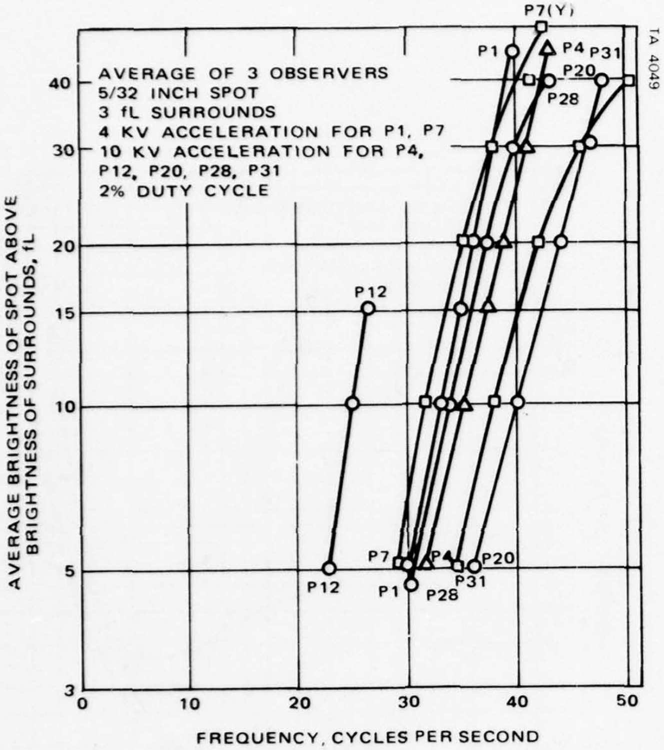


Figure 3-15. Pulse modulation critical fusion frequency.

methods to predict relative flicker characteristics of several phosphors. Turnage restricts his analysis to a rank-ordering of phosphors in terms of degree of flicker suppression, based on the rule that the least flicker is produced for a given repetition period by a phosphor having the highest percentage of its peak light output remaining one period following the removal of excitation. The seven phosphors employed by Turnage were ranked in the following order: P12 (least flicker), P7, P1, P28, P4, P31, P20 (most flicker). Turnage cautions that P20 did not have the persistence characteristics published by the Electronics Industries Association.

Krupka and Fukui (1973) extended the analysis to predict relative CFF values by performing a series of Fourier analyses on phosphor persistence curves and plots of the temporal sensitivity of the visual system similar to the one presented in Figure 3-3. In general, their ranks agreed with those of Turnage; where discrepancies occurred, the inclusion of visual system characteristics appeared to lead to a more accurate prediction. Details of their method may be found in their article.

The extremely short rise and decay time of light-emitting diodes (LEDs), on the order of nanoseconds, requires a much higher refresh rate than typically required with CRT displays employing phosphors. For example, with a 1 in. x 1 in. monolithic gallium phosphide (GaP) LED array, a refresh rate of 200 Hz is employed by Monsanto Corporation to eliminate flicker, while with a 6 in. x 6 in. multicolor GaP LED display, Litton Data Systems refreshes the display at a rate of

1000 Hz.

When motion is simulated on an LED display, or the display or observer is moving (as in a vibrating environment), multiple images may result even at refresh rates sufficient to prevent flicker. This phenomenon has also been observed with CRT displays, and will occur when the imaged information is moved between successive refresh or update rates, so that the stimulus elements will strike different locations on the retina.

Riley (1977) conducted a study in which the refresh rate of a GaP LED display was varied between 60 and 1200 Hz. Both the display and subjects were vibrated in the vertical direction by means of a shake table reflecting the motion of combined 2, 5, 10 and 14 Hz sine waves. Subjects viewed pairs of horizontal lines formed by two rows of diodes, each approximately 3^{o} of visual angle long and 2' high. Each line within a pair was presented for 3 seconds with a 4-second interstimulus interval, and each pair consisted of two different refresh rates. Rates of 60, 200, 400, 500, 600, 700, 800, 1000 and 1200 Hz were presented so that each rate was paired with every other rate. Subjects judged whether the first or second line of each pair showed the least multiple imaging.

The results are presented in Figure 3-16. The

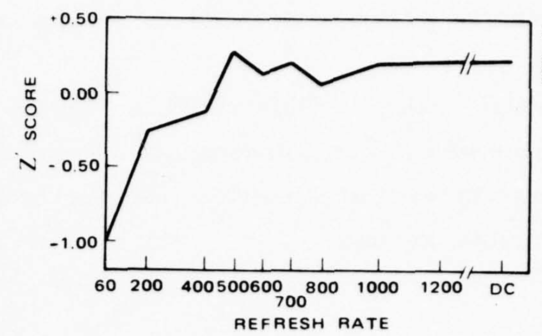


Figure 3-16. Multiple imaging as a function of refresh rate.

only statistically significant difference found was between a 60 Hz refresh rate and every other; inspection data the data, however, indicates that preferences asymptote around 500 Hz. No data regarding the effect of multiple images on performance was obtained.

Scanlan and Carel have suggested that multiple imaging may be explained within the context of Stroud's (1955) psychological moment concept. Details of this conceptualization have been presented previously. Assuming a time frame or visual integration period of 100 ms, Scanlan and Carel (1976) argue that multiple images will be seen "when successive displacements of intermittent images exceed the visual acuity threshold within an interval of 100 ms." They present the example of a spot updated at a rate of 100 Hz and displaced 2 arc minutes between each update; the perception of 10

spots separated by 2 arc minutes in 100 ms is predicted.

The relationship is illustrated in Figure 3-17 for a time frame of 100 ms, three acuity thresholds and for an image moving at velocities ranging from 0.1 to 100 arcminutes/second.

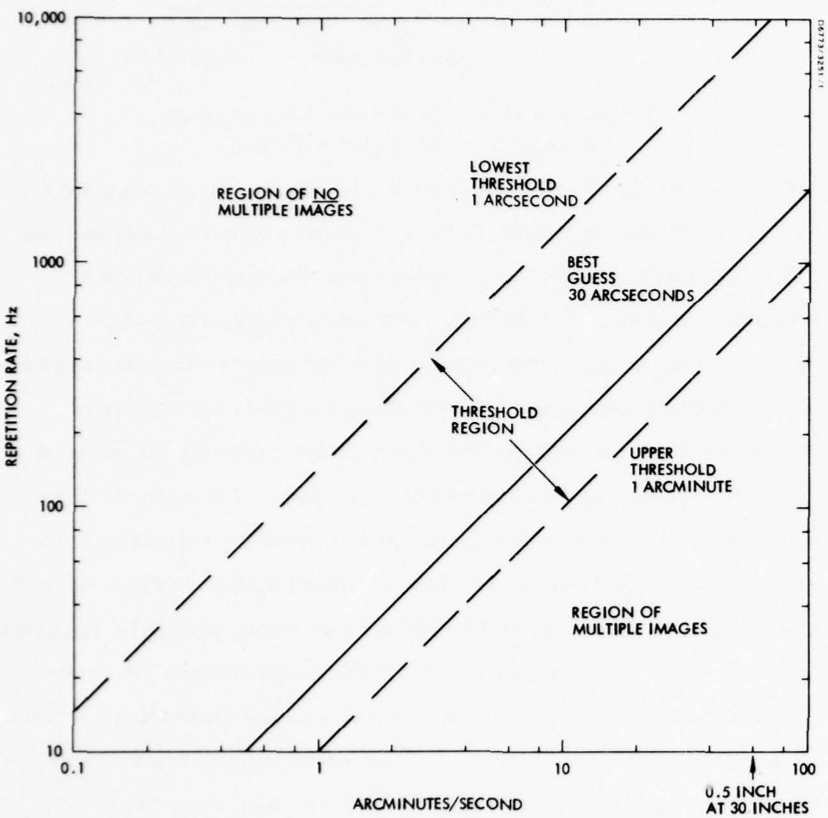


Figure 3-17. Conditions for multiple images in LED type displays.

The elimination of flicker, while an important design criterion in itself, cannot be optimized in isolation. Increasing refresh rates and/or phosphor persistence will successfully overcome flicker problems, but will involve tradeoffs with other display parameters, particularly in sensor displays where apparent motion is to be produced. For example, increasing the refresh rate decreases information capacity, while increasing phosphor persistence, may lead to smearing at update rates required by the task. These tradeoffs will be discussed more fully in the context of motion perception.

3.6 SUMMARY

The following three conclusions seem appropriate:

Flicker is annoying and may degrade performance, particularly perceptual-motor coordination. Every effort should be made to avoid it. Distraction, visual fatigue and degraded motor performance will occur at the lowest flickering frequencies (1-8 Hz); in the range of 8-10 Hz epilepsy may be induced in susceptible individuals; at higher frequencies, dizziness, nausea and other performance-hindering reactions may be induced.

The visual system works as a low-pass filter with respect to temporal frequency, with maximum sensitivity in the range of 10 to 30 Hz. Flicker is

generally perceived under any conditions below 20 Hz, but rarely detected at frequencies beyond 60 Hz because of the minimal sensitivity to high frequency. However, the upper limit may rise to as much as 80 Hz in situations that include extremely high illumination (bright sunlight), a large display area and with the use of short persistence phosphors.

Factors that will decrease the necessary refresh rate will include decreasing display size, ambient illumination or display luminance. Display luminance may be decreased by a reduction in the amount of information displayed or in the update rate, or by filtering the short component of cascade phosphors. A small reduction in the CFF may be found with relatively large increases in the light to dark ratio, if overall luminance is held constant. The necessary refresh rate will also be reduced by the use of longer-persistence phosphors, but their use may be constrained by smearing effects when rapid apparent motion is displayed (high update rates). The minimum refresh rates necessary to eliminate flicker with representative long (P12) and medium (P31) persistence phosphors are presented in Figure 3-18 for three display sizes over a wide range of luminance values. Refresh rates for the field of view subtending 0.6° of visual arc were empirically determined by Turnage (1966); the

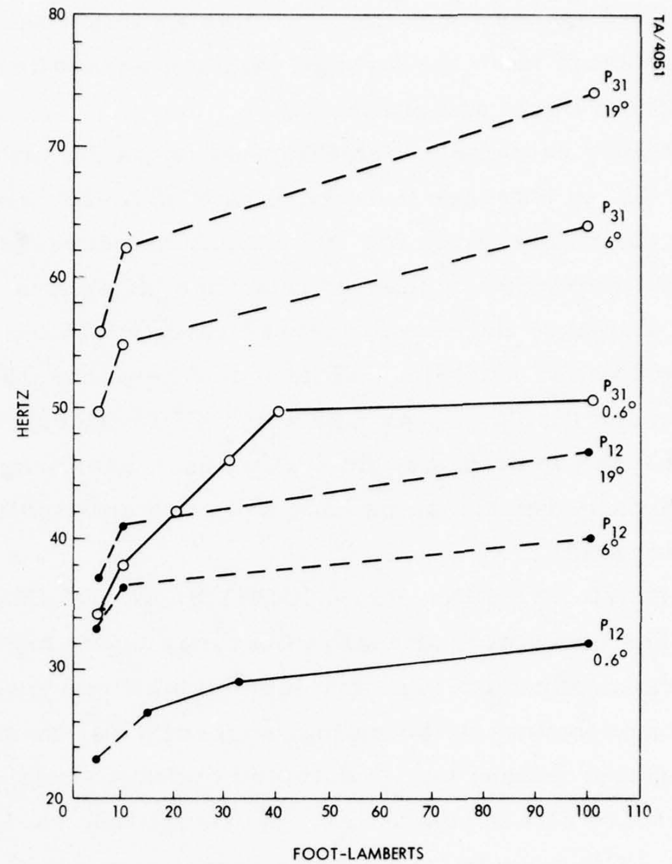


Figure 3-18. CFF values for long (P12) and medium (P31) persistence phosphors, pulsed at a 2 percent duty cycle with three display sizes in degrees of visual arc. Solid lines represent data from Turnage (1966); broken lines predicted from Turnage data and Hecht and Smith (1936).

predicted values for 6° and 19° display fields were extrapolated from the Turnage data and area-effect data from Hecht and Smith (1936).

Under extremely high illumination on the order of 1000 fL, an increase in refresh rate of 12-25 percent from the values given for 100 fL may be necessary.

With extremely short persistence phosphors or LED displays, necessary refresh rates will vary between 200 and 1000 Hz. While it is likely that illumination and display areas will affect CFF values with these types of displays, no studies have been found in which these relationships have been systematically investigated.

3.7 REAL MOTION: PSYCHOPHYSICAL STUDIES

The perception of real motion may occur under several conditions. The eye may be stationary while an image traverses the retina; successive stimulation of adjacent retinal loci is detected by large-field cells specific to direction and velocity (Hubel & Wiesel, 1962). Conversely, the eye may track a moving target; the image is then stationary on the retina. Eye movements are sensed by the observer, but positional cues are not precise enough to provide the information that is known to be available to the observer (Spigel, 1965). Because of this, it is extremely difficult to detect motion without some frame of reference. However, even in a homogeneous field, it is possible to detect a change in position over time, from which motion may be inferred.

3.7.1 Velocity Thresholds

Some evidence for the greater efficiency of detection with context cues present may be found from velocity threshold studies, in which the minimum velocity that can be detected is determined. In a homogeneous field, the velocity threshold is about 18 arc-minutes of visual arc per second (min/sec) for a 500 millisecond exposure, decreasing to a minimum of 9 arc-minutes/sec with a 16-second exposure (Brown & Conklin, 1954). On the other hand, in a field containing stationary objects or a frame surrounding the visual field, the velocity threshold is reduced to as low as 30 sec/sec (Graham, Baker, Hecht, & Lloyd, 1948). The large threshold difference between these two viewing situations implies two separate processes may be employed for motion detection. The reduction in the threshold found with referents available indicates that efficient motion detection involves a comparison among different parts of the visual field. There is also evidence that efferent commands controlling eye movements interact with the resulting visual input to produce the perception of movement (von Holst, 1954; Gyr, 1972). For example, movement appears to be faster when the eyes are

fixated on a stationary locus than when they are tracking a moving target by a ratio of 1.43 to 1.0 (Graham, Baker, Hecht, & Lloyd, 1948).

Velocity thresholds will vary with a number of additional parameters. Lower thresholds are found with increased contrast, exposure time, and field size (Brown, 1955; Haber & Hershensen, 1973; Leibowitz, 1955) as well as with movement in the horizontal direction (Graham, Baker, Hecht, & Lloyd, 1948). At low levels of luminance, decreasing threshold velocities are found as luminance increases. At moderate intensities, however, duration of exposure is a more important variable (Leibowitz and Lomont, 1954). This relationship is illustrated in Figure 3-19 for a target subtending 15 minutes of visual arc.

As velocity increases, an upper threshold is reached beyond which visual acuity decreases, beginning at an angular velocity of about 13°/sec for a small target when the head is stationary (Ludvigh, 1956) and increasing up to 40°/sec with free head movements or if the target is first presented in a stationary position (Smith & Gulick, 1957, 1962).

3.7.2 Dynamic Visual Acuity

The relationships between dynamic visual acuity and angular velocity, dynamic and static visual acuity, and dynamic acuity among individuals were examined

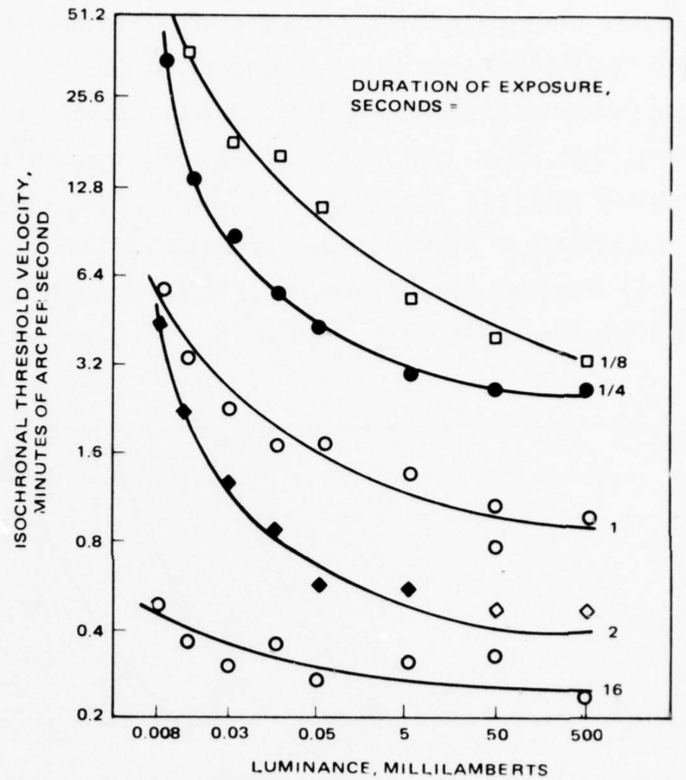


Figure 3-19. Isochronal threshold velocity as a function of luminance level and duration of exposure (Semple, 1971).

by Ludvigh & Miller (1958). Landolt C Rings were presented at angular velocities ranging from 10^{0} to 170°/sec, with the critical detail gaps varying between 0.75 and 11.25 minutes of arc. Illumination on the targets was held constant at 25 footcandles.

Subjects, viewing from a distance of 4 meters, were to locate the orientation of the gap in the Landolt ring. Subjects were divided into three groups based on pre-test performance, and were tested up to maximum velocities of 110°, 140°, and 170°/sec. The results are presented in Figure 3-20, and are indicated by the circles, squares, and triangles; the lines were generated from the equation $y = a+bx^3$.

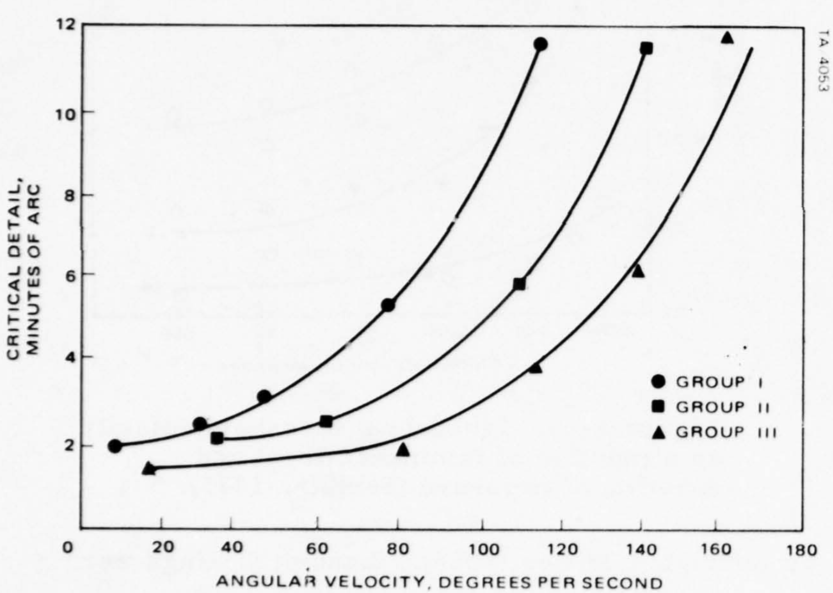


Figure 3-20. Threshold values for all subjects grouped according to pre-test performance levels (Semple, 1971).

where y is visual acuity in minutes of arc, x is the angular velocity in degrees per second, and a and b are constants whose values were not specified. It can be seen that a great amount of detail is lost at extremely high velocities. For simple detection tasks, this loss may not be critical; recognition tasks requiring finer discriminations, on the other hand, will suffer when the target is moving at an extreme velocity.

Dynamic visual acuity, similar to velocity thresholds, is slightly better when movement is in the horizontal direction. A consistent advantage of one to two minutes of arc is found over a wide range of angular velocities, as illustrated in Figure 3-21 (Miller, 1958). Dynamic acuity may also be improved by high intensities of illumination. With an angular velocity of 90°/sec, Ludvigh (1949) found continually improving acuity at levels as high as 505 footcandles. Although it is suggested that acuity will improve at even higher levels, there is little available data to support this supposition. Further research is necessary to determine the effect of illumination levels similar to those of bright sunlight.

Large individual differences are found in dynamic acuity, and little, if any, relationship exists between static and dynamic acuity. For example, the two dynamic acuity curves presented in Figure 3-22 were

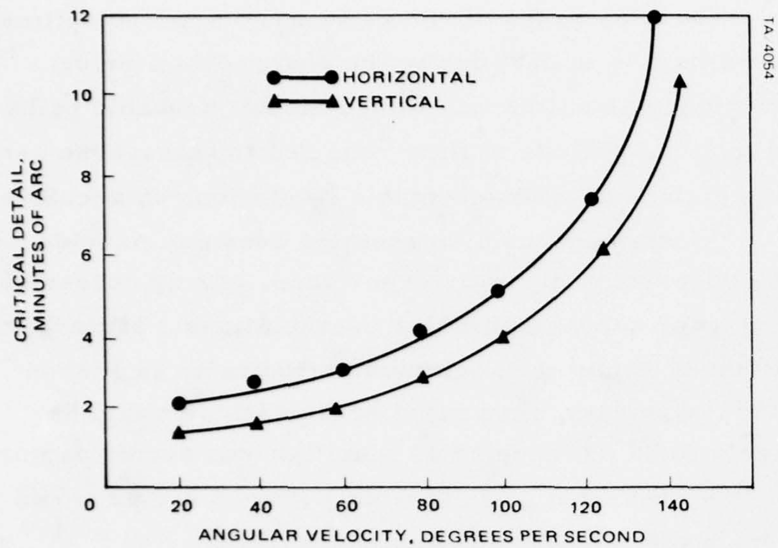


Figure 3-21. Visual acuity as a function of horizontal vs vertical movement (Semple, 1971).

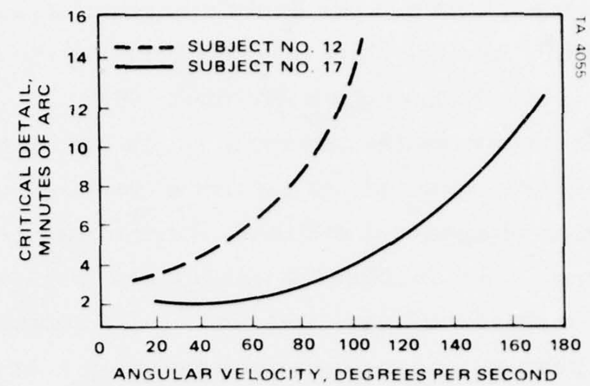


Figure 3-22. Difference between two subjects in degradation of dynamic acuity with increasing angular velocity (Semple, 1971).

both obtained from subjects with 20/20 (Snellen) static acuity. In addition, situational factors such as visual fatigue, age and anoxemia will deteriorate dynamic acuity (Semple, Heapy, Conway & Burnette, 1971).

3.8 APPARENT MOTION

Experimental results resulting to real motion are in many cases relevant to the perception of apparent motion, although display factors such as phosphor persistence will interact with some of the variables previously discussed, and in practice, other display considerations may require tradeoffs resulting in less than optimal apparent motion.

Apparent motion is perceived when a series of static but spatially displaced stimuli are successively presented. Investigations of apparent motion have been in general concerned with the quality of motion between two spots of light; subjective judgments were made as to whether the two images appeared to be presented simultaneously, successively, or whether motion between the two locations was perceived. Manipulated variables have included size, color, and luminance of the flashes (Korte, 1915; Squires, 1931), spatial

displacement between the spots, length of exposure to the stimuli, and the time interval between the flashes (Korte, 1915; Kahneman & Wolman, 1970).

The interstimulus interval, which corresponds to an interframe interval, is a critical variable in the perception of apparent motion. Wertheimer (1912) found that if two successive images are presented within a 30-millisecond dark interval of one another, they will be seen as occurring simultaneously. At the other temporal extreme, if the intervening interval exceeds 200 milliseconds, the stimuli will be perceived as two static, successive images. Under these conditions, it may be impossible to determine whether or not any target has been displaced (Pollack, 1972 a, b) due to immediate memory limitations for spatial position. Between these two extremes, optimal temporal spacing will result in the perception of smooth motion. For his particular conditions, Wertheimer found this interval to be 60 milliseconds; at shorter or longer intervals between the two extreme values, partial and dual movement was observed. Under other conditions, however, the 60-millisecond value will not produce the smoothest perception of motion. For example, Nehaus (1930) found optimum values ranging between 80 and 400 milliseconds for certain stimuli exposure durations and spatial separations.

The wide range of values found to produce optimal movement is in part due to the observer's a priori knowledge about the way things move: probable paths of motion, periods of time required to transverse certain distances, and acceptable limitations on acceleration. Instantaneous displacement does not coincide with the observer's previous experience, nor do excessively long gaps between stimulus presentations. Moreover, if visual stimuli are sampled periodically as Pieron (1952) suggests, then rapid presentations would be likely to be interpreted as simultaneous events captured by one "snapshot", while widely spaced events would reasonably be perceived as unconnected.

Korte (1915) described the relationships among the temporal pause between two stimuli, the luminance of the stimuli, the exposure time of the stimuli, and the spatial separation between the stimuli in a series of statements often referred to as Korte's Laws. Their validity, however, is questionable when luminance is varied since as Kohlers (1972) points out, size, figural detail, and intensity all contribute to Korte's luminance category. Graham (1965) presents these laws as follows: For optimal apparent movement, the threshold value of

1. Spatial separation increases as luminance increases, with the intervening interval and exposure

time remaining constant.

2. Luminance decreases as the intervening interval increases, with the spatial separation and exposure time remaining constant.

3. Spatial separation increases as the intervening interval increases, with luminance and exposure duration held constant.

4. Exposure time decreases as the intervening interval increases, with luminance and spatial separation held constant.

Nehaus (1930) presented evidence in accord with the third and fourth laws, but found no change in the other variables necessary when stimulus intensity was varied over a wide range of values.

3.9 APPARENT MOTION: APPLIED STUDIES

Until relatively recently, the lower bound on the rate of presentation of new information was determined by the refresh rate and flicker considerations. However, technological advances in the last decade have made it feasible to separate refresh rate from update rate; there is considerable evidence from the psychophysical studies that the perception of apparent motion does not require new information at the rates of 50 or 60 Hz, values commonly found for refresh rates. In addition, task requirements may not even demand the perception of smooth motion, but only an intermittent updating of information allowing the observer to view ahead both in time and space. An additional consideration of some importance is the rate at which the observer samples the information presented. In many situations attention is shared among several tasks not dependent on the display of interest. This observer-imposed intermittency will affect information update rate considerations.

3.9.1 Time Compression

A somewhat different aspect of the problem involves the detection of motion in slow refresh systems such as radar. While slowly moving targets may appear to change position in a coherent manner against a background of random noise or stationary clutter, it has been demonstrated that the technique of visual time compression may greatly enhance detectability as well as produce information from objects that appear to be random noise under normal conditions (Chandler and Harris, 1970; Moll & Scanlan, 1972). In time compression systems, stored frames are successively presented at a rapid rate to enhance motion detection, and are intermittently updated by replacing the oldest stored frame with the newest from the radar processor. A rapidly moving pattern then slowly traverses the display screen, simultaneously highlighting motion and keeping the display current. While many of the variables

investigated in time compression studies are not relevant to the present discussion, motion detection will be affected by exposure time of the stimulus, the interstimulus interval, and the spatial separation of the stimuli. These variables have direct analogs in visual time compression: frame duration, interframe interval, and target return spacing. Scanlan (1975) varied these three factors as well as the number of stored frames in a study using a radar display with only two levels of brightness, although the results may tentatively be generalized to displays with multiple gray shades. This, however, remains to be experimentally verified.

Scanlan's results are presented in Figures 3-23

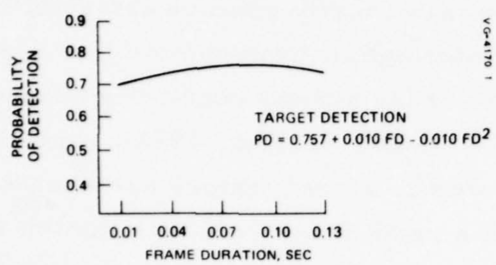


Figure 3-23. Effect of frame duration (FD) on the probability of correctly detecting a target (PD).

through 3-26. Two interactions not illustrated by these figures are that as inter-frame intervals decreased,

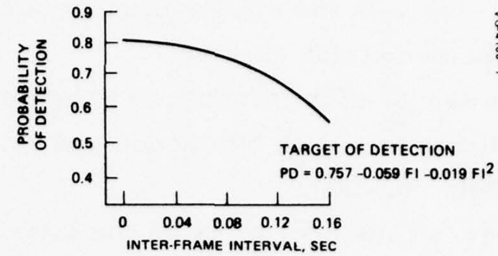


Figure 3-24. Effect of inter-frame interval (FI) on the probability of correctly detecting a target (PD).

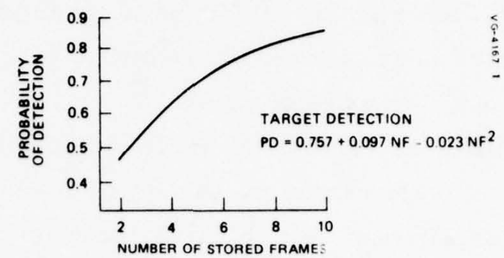


Figure 3-25. Effect of number of stored frames (NF) on the probability of correctly detecting a target (PD).

the target return spacing necessary for the best target detection decreased; and the optimum frame duration increased with decreasing inter-frame intervals. The best performance was obtained with zero inter-frame

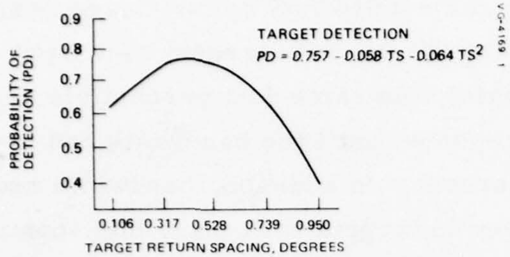


Figure 3-26. Effect of target return spacing (TS) on the probability of correctly detecting a target (PD).

interval, which would not be predicted from the psychophysical studies on motion perception. In addition, the highest ratings of apparent motion were obtained with very short inter-frame intervals.

The discrepancies found in the Scanlan (1975) study from predictions from the apparent motion literature exemplify the hazards in generalizing from limited laboratory studies to applied situations. Unfortunately, very little applied work has been done relating the quality of apparent motion, update rates, task requirements and task performance.

3.9.2 Motion and Target Detection

In a study conducted by Erikson, Hemingway, Craig & Wagner (1974), dynamic visual acuity was measured as a function of image velocity, gap orientation, and the number of scan lines per gap width on a 525-TV-line system. A refresh rate of 30 Hz with a 2:1 interlace was used to yield a field rate of 60 Hz, and the bandwidth of the system was kept constant at 10 MHz. Ambient illumination was quite low (3 foot-candles). The percent of correctly identified gap orientations (averaged over all orientations) is shown in Figure 3-27. In general, acuity decreased with increasing

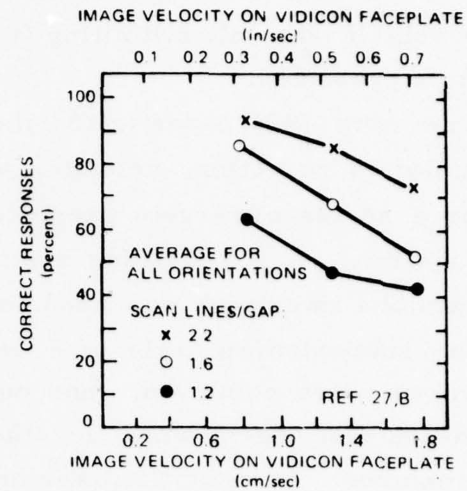


Figure 3-27. The effect of image motion on the detection of orientation of a Landolt ring in a TV display averaged overall orientation (Farrell, 1975).

image velocity, and was better with a greater number of scan lines per gap. *However, the orientation of the*

gap produced considerable differences; the results for the four orientations are presented in Figure 3-28.

In a second study, observers attempted to discriminate between moving military vehicles and clutter objects similar in size and shape. Velocity and scan lines per vehicle were manipulated, and the results of this experiment are presented in Figure 3-29. Performance was poorer at higher velocities; the number of scan lines per vehicle was only a limiting factor at the lower velocities presented.

Connor and Berrang (1974) investigated the relaship between bandwidth reduction, velocity, and image quality for a series of targets presented sesequentially on a CRT. A 271-TV-line system with a 30 Hz frame rate (2:1 interlace) was used in the study; the display subtended an angle of 8 degrees. Two types of targets were employed; one contained many high-contrast edges, while the other had only a few such features. At velocities ranging from 0^{o} (stationary) to 4.4^{o}/sec, subjects rated the image quality of the targets transmitted at bandwidths varying between 0.20 MHz and 0.80 MHz against standards transmitted at 1.0 MHz. The major result indicated that for targets in motion, much greater reductions in bandwidth can be tolerated than for stationary targets. For example, a 37 percent reduction in bandwidth was necessary for subjects to just notice image degradation with a stationary target; with targets moving at 4.4^{o}/sec (visual angle), the same just perceptible degradation was not reported until the bandwidth had been reduced by 63 percent. In addition, bandwidth reduction had more effect on targets with many high-contrast edges. These results are presented in Figure 3-30.

3.10 UPDATE RATE

The major consideration in the determination of update rate is the task requirement. In some continuous-control tasks, the perception of smooth apparent motion may be *critical*, while *tasks* involving target detection may be less dependent on the quality of the motion perceived than on allowing the observer enough time to search the currently displayed scene. The response to the displayed information, then, is also an important consideration. Such factors as the nature of the displayed information (cluttered or relatively homogeneous; dynamic or relatively static), the task, and the amount of time available for the observer to respond to the displayed information will all be necessary considerations in the determination of update rate. The anticipation interval (Carel, 1965), or how far ahead the observer can see in space and time, is also a factor. In general, the larger the interval, the less need there is for rapid updating. A further consideration is

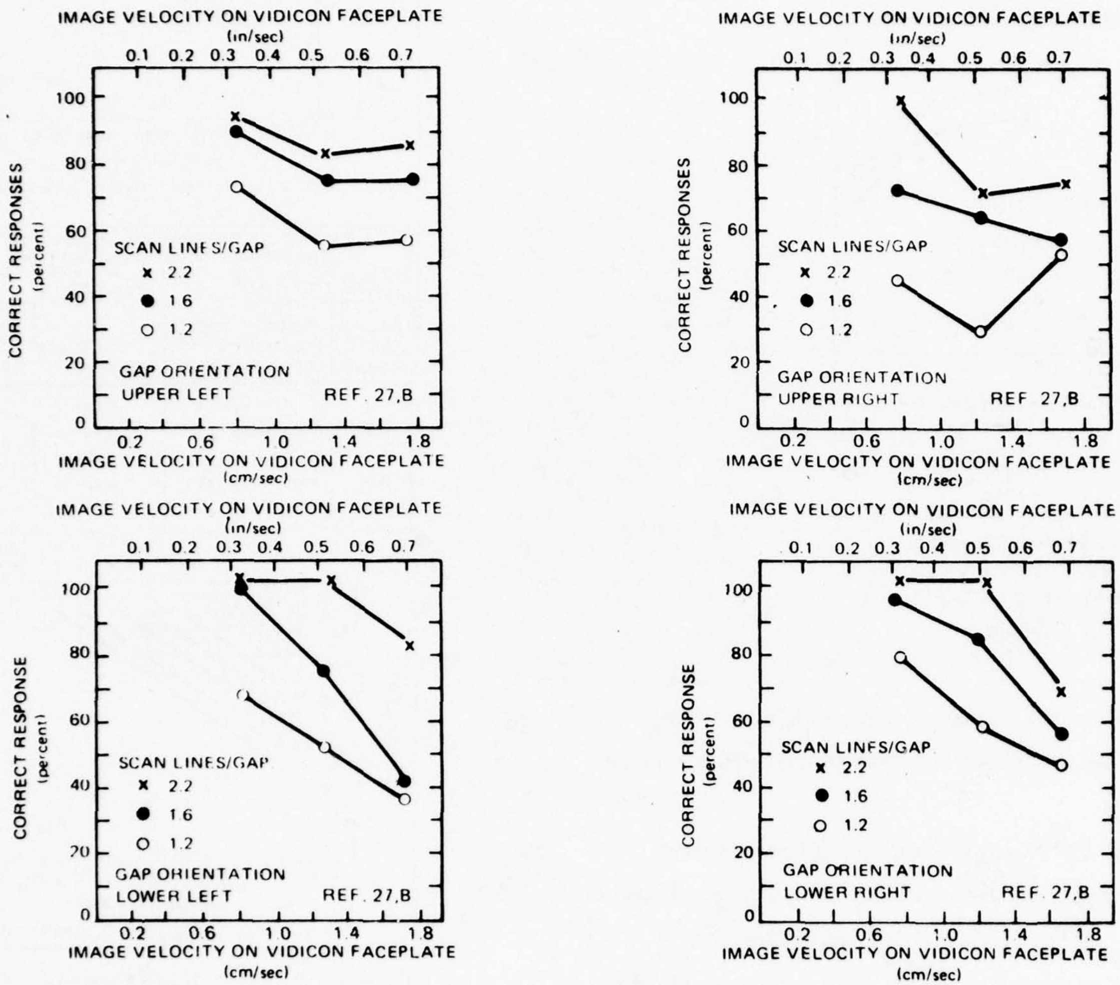


Figure 3-28. The effect of image motion on the detection of orientation of a Landolt ring in a TV display (for individual orientation) (Farrell, 1975).

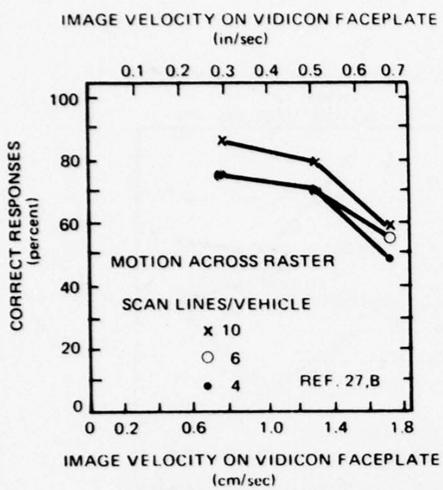
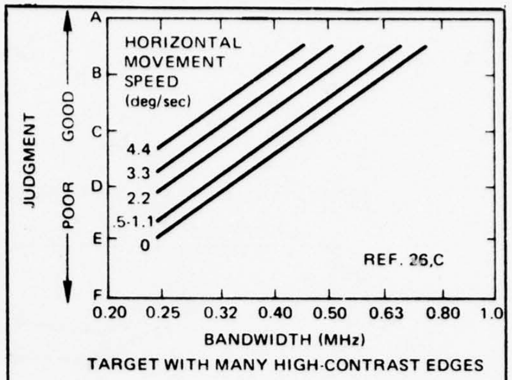


Figure 3-29. The effect of image motion on the identification of vehicles displayed on a CRT (Farrell, 1975).



BANDWIDTH REDUCTIONS CAUSING JUST PERCEPTIBLE IMAGE DEGRADATION				
IMAGE MOTION		BANDWIDTH		
VISUAL ANGLE (deg/sec)	FRAME WIDTHS/ SEC	TEST SCENE (MHz)	COMPARISON SCENE (MHz)	PERCENT REDUCTION (test comparison)
0	0	1.0	0.63	37
~0.5-1.1	0.23–0.45	1.0	0.56	44
2.2	0.27	1.0	0.48	52
3.3	0.41	1.0	0.42	58
4.4	0.54	1.0	0.37	63

(b)

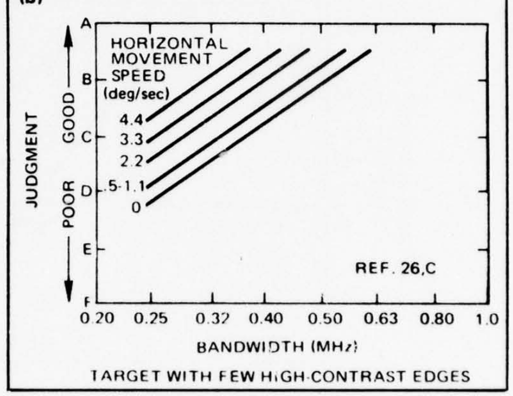


Figure 3-30. Relationship between bandwidth, image motion and judged image quality (Farrell, 1975).

the sampling rate of the observer. Carel states that the update rate must be at least twice the response rate of the observer.

Display variables such as phosphor persistence and refresh rate will also be necessary considerations in determining update rate. When the information presented is changing rapidly, short persistence phosphors may result in an undesirable jumping effect, while long persistence phosphors will produce trails

following moving objects, possibly obscuring critical details of the display. Bandwidth tradeoffs will be necessary with increases in either update or refresh rate, and a higher update rate will produce a higher overall luminance (Semple, Heapy, Conway, and Burnette, 1971), which in turn may require an increased refresh rate.

Senders (1955) investigated the effects of information presentation rate on performance of tracking tasks in an early study that unfortunately contained confounding effects of flicker. Subjects were to track two pointers, each in separate instruments, under intermittent illumination. The frequency of illumination was varied between 4 and 20 Hz, and lighttime fractions between 0.05 and 0.50 were employed. In general, time on target increased with increasing frequency of presentation of information, as well as with increases in the light-time fraction. These results are summarized in Figures 3-31 and 3-32. However, it is difficult to separate the effects of flicker from the effects of information update rate in this experiment. Several studies, however, have been conducted to examine the effect of update rate on image quality and performance. In one study confined to subjective judgments of motion quality, Brainard, Mounts and Prasada (1967) used a TV monitor to display an image of the head and

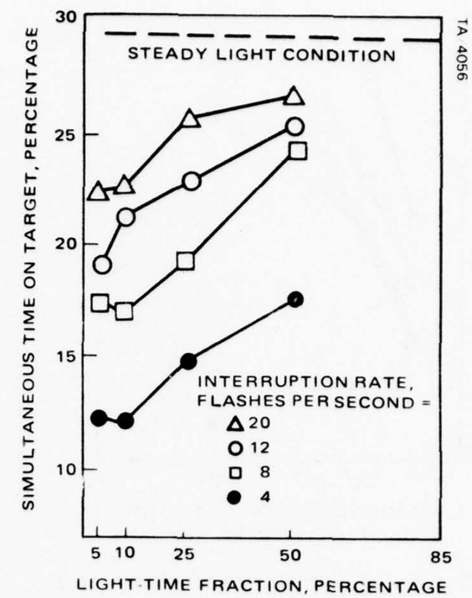


Figure 3-31. Performance as a function of flash duration (Senders, 1955).

shoulders of a human moving and talking at natural speeds. The video signal was generated by a vidicon camera system which sequentially scanned the vidicon at 60 frames per second with a raster of 160 lines. With the refresh rate maintained at 60 Hz to eliminate flicker effects, new information was presented at rates of 30, 20, 15, 12, 10, 8.6, 7.5, 6.7 and 6 new pictures/second.

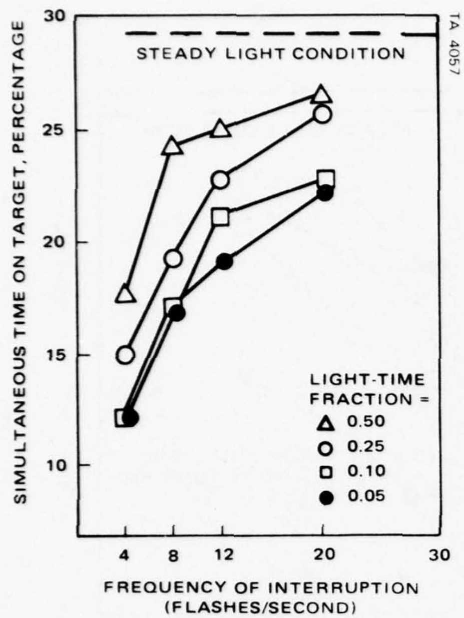


Figure 3-32. Performance as a function of information presentation rate (Senders, 1955).

No image degradation was reported at the highest update rate used. At 20 new pictures/second, large-area slow motion (head movements) produced a small amount of jerkiness. At 15 new pictures/second, the large area jerkiness was noticeable, but smaller, more rapid movements produced by lip motion were unaffected. Below 12 new pictures/second, even small area motion produced bothersome jerkiness. It was concluded that in systems with frame repeating, update rate could be reduced to between 12 and 15 new pictures/second while still maintaining acceptable image motion.

For many tasks, smooth image motion may not be necessary for adequate task performance. Outer loop control functions such as navigation and mission planning which are sampled infrequently require only very infrequent update rates, on the order of seconds or minutes. On the other hand, to maintain control of rapidly changing characteristics such as bank angle or any parameter that tends toward instability, rapidly updated information is required.

In a task designed to simulate the latter situation, Hughes Aircraft Laboratories (1977) compared performance with a finger operational force control when update rate of information displayed on a CRT was continuous to performance at rates ranging between 5 and 60 Hz. Subjects were given extensive training with the control in situations where the system became instable and the control was to be regained on the basis of displayed information. The results from two subjects are presented in Figure 3-33. Although full capability is not realized even at a 60 Hz update, nearly 85 percent of performance obtained with continuous updating is found at a 20 Hz rate.

Self and Heckart (1973) examined RPV operator

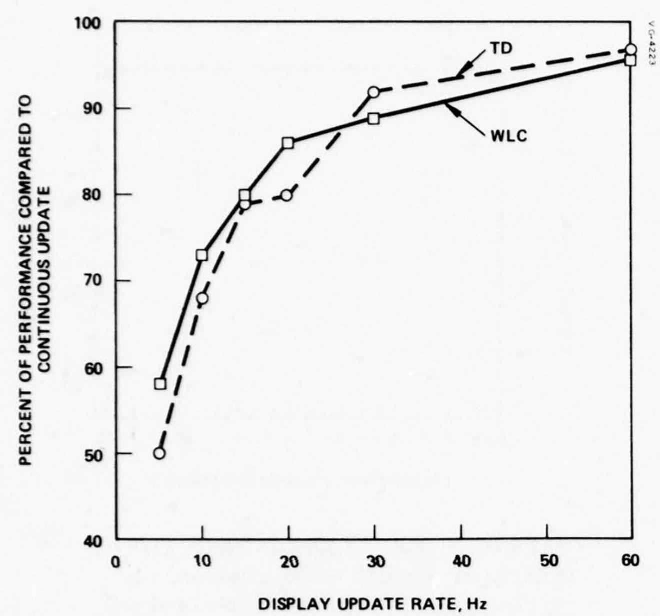


Figure 3-33. Tracking performance on a critical task as a function of update rate for two well trained objects.

target recognition performance at update rates of 1, 3, 8 and 24 frames/second. Their results, presented in Figure 3-34, indicate that update rates as low as 1 frame/second do not significantly degrade recognition performance.

Higher frame rates appear to be necessary for target acquisition (sensor pointing to lock-on to the target) tasks. The results of four articles reviewed

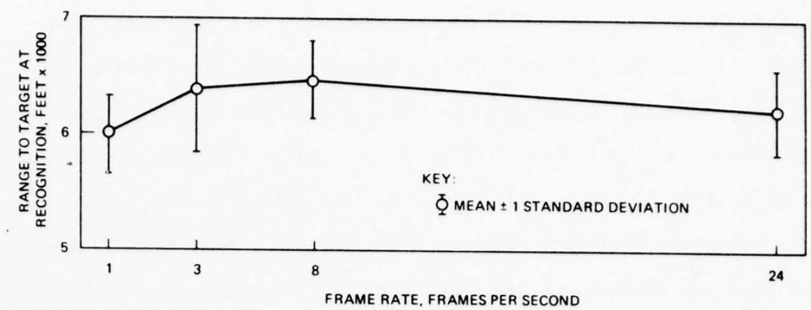


Figure 3-34. Effect of video frame rate on operator target recognition performance.

by Hillman (1967) provided estimates ranging from 2 to 7.5 frames/second as the lowest acceptable rates for acquisition tasks.

In a series of studies designed to investigate band-width reduction/compression for remotely piloted vehicles, Hershberger and Vanderkolk (1976) manipulated video frame rate and sensor control modes in order to examine the effects on target recognition and acquisition. The four frame rates in the first study were 0.23, 0.94, 3.75 and 7.5 frames/sec., while the control modes were 3-axis stabilized sensor pointing, 3-axis stabilized with motion compensation, and cursor designation. Details of the sensor modes are given in their report.

Temporal sampling of the video created a delay between the control command and the displayed image

sensor response of two update frames. The lower the update rate, the longer the elapsed time before the results of the command were visible. This delay was found to be a significant factor in reducing target recognition at the lowest update rate, but when the effects of this delay were removed, it was determined that frame rate had no effect on recognition performance. The results including and excluding the delay effects are presented in Figures 3-35 and 3-36, respectively. With

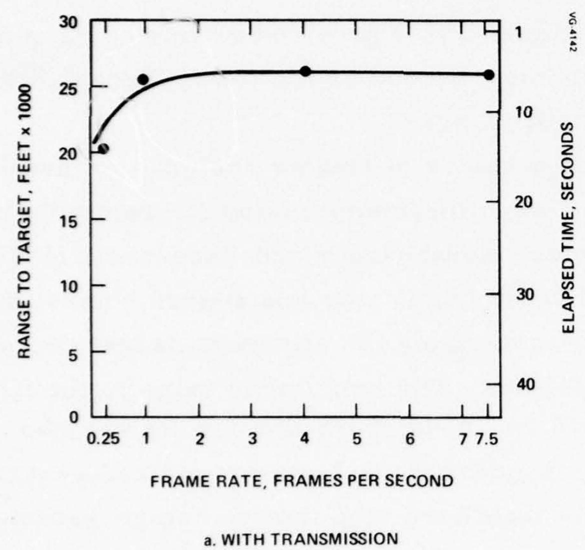


Figure 3-35. Frame rate effects on operator target recognition performance.

the delay effects removed, these results agree with and extend those of Self and Heckart (1973); it was

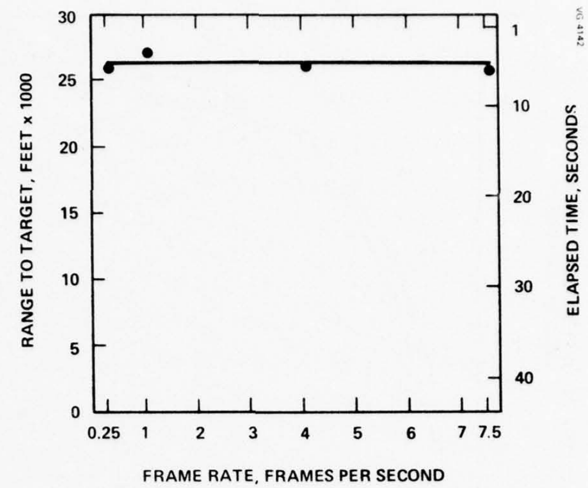


Figure 3-36. Frame rate effects on operator target recognition performance with transmission delay taken out.

concluded that update rates as low as 0.23 frame/second did not degrade target recognition performance.

No effect of sensor control mode was found on recognition performance, which is to be expected, since little, if any, pointing was required for the task. The control mode, however, did interact with frame rate in the target acquisition task. Low update rates did not degrade acquisition performance with the cursor designation mode nor with the 3-axis stabilized with motion compensation mode. However, with the unaided 3-axis

stabilized system, acquisition performance was severely degraded at update rates below 3.75 frames/second. These data are presented in Figure 3-37.

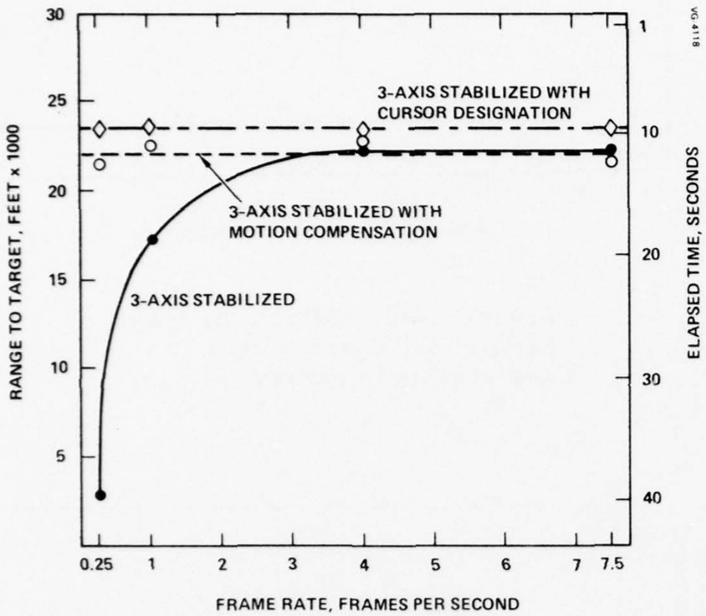


Figure 3-37. Effects of frame rate and control mode on operator target acquisition performance.

Performance on the combined target recognition and acquisition tasks is shown in Figure 3-38. No differences are found among the three sensor modes at update rates of 3.75 and 7.5 frames/second, but at slower rates, performance is degraded. Although the

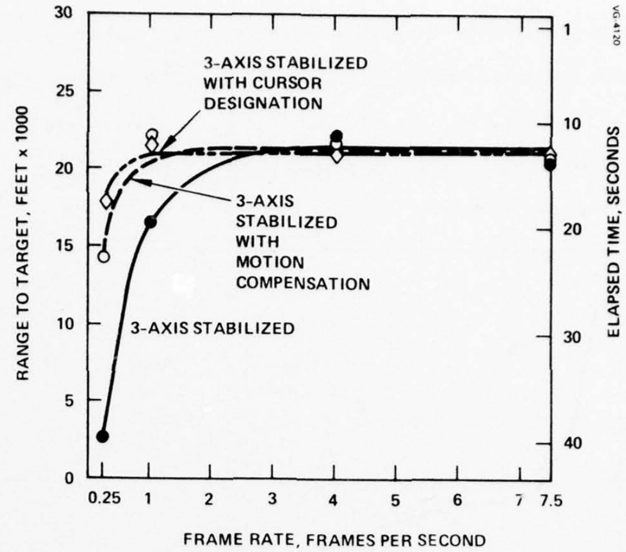


Figure 3-38. Effects of frame rate and control mode on combined operator target recognition and target acquisition performance.

degradation is not as substantial with aided control modes, some loss in performance will occur due to the great information delay incurred with low update rates.

A second study in the series increased the precision with which sensor pointing was to be made, and again manipulated the effect of update rate on task performance — in this case to designate a moving target and to track it for 35 seconds. Accuracy rather than time was stressed, and the authors point out that the

accuracy data and relative rather than absolute time data are more useful. Six update rates were used with the values of 0.94, 1.88, 3.75, 7.5, 15.0 and 30.0 frames/second. The results are presented in Figures 3-39 through 3-41.

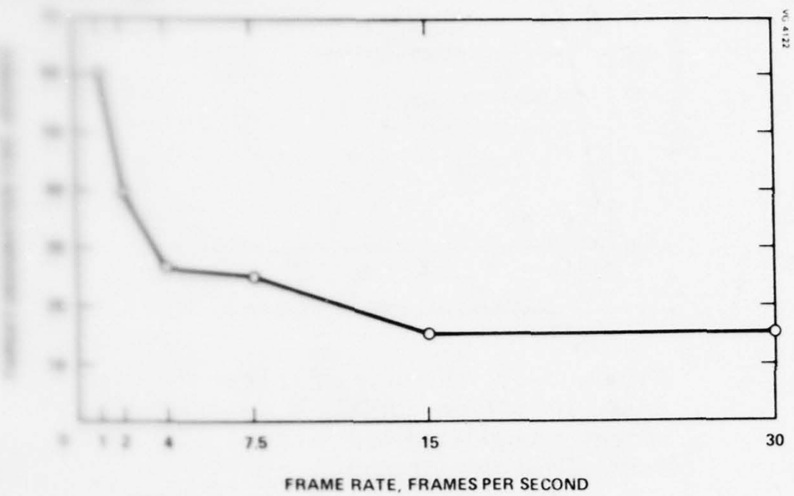


Figure 3-39. Effects of frame rate on target designation time.

Figure 3-39 illustrates the relative difficulty of the target designation task as a function of update rate. Substantial gains in time result from update rates increased to 3.75 frames/second; the 0.94 and 1.88 frames/second values make the task extremely difficult to perform. The relationship between update rate and radial designation error is shown in Figure 3-40. No reliable differences were found among rates between

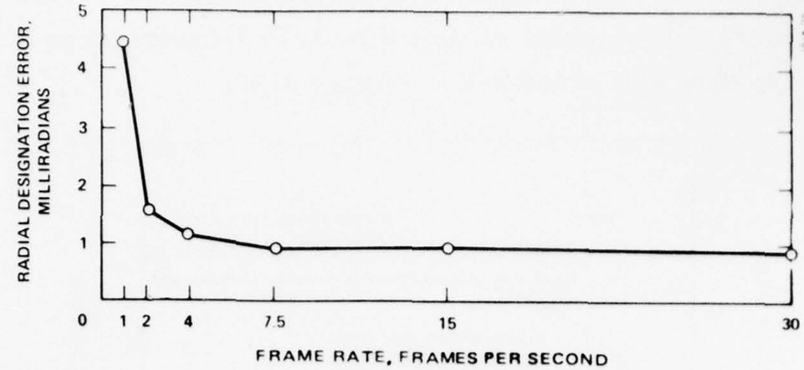


Figure 3-40. Effects of frame rate on precision target designation accuracy.

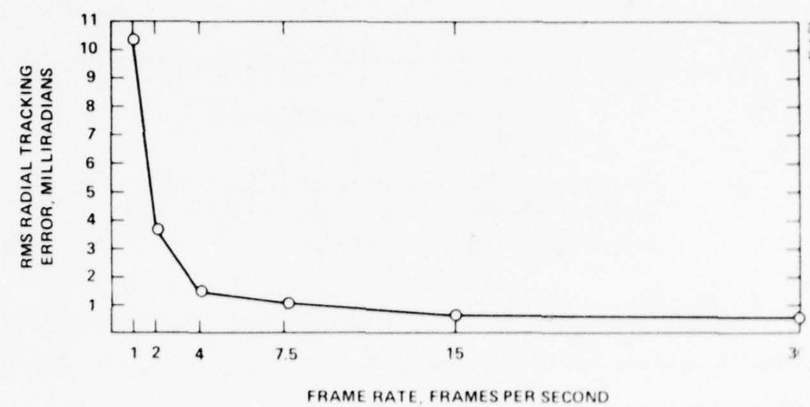


Figure 3-41. Frame rate effects on target tracking accuracy.

1.88 and 30 frames/second; only the lowest update rate significantly degraded accuracy of precision target designation.

Similar results were obtained with the effect of frame rate on tracking accuracy shown in Figure 3-41. The major improvement was found with an increase up to 3.75 frames/second; beyond this value only minimal gains were incurred.

A third study, in which sensor video resolution, optical zoom and update rate were varied to determine their effects on target recognition and acquisition, did not indicate any effects due to frame rate. Rates of 0.23, 0.94 and 7.5 frames/second were employed with the 3-axis stabilized with motion compensation control mode. The major findings of this study pertinent to update rate was the lack of an interaction between zoom and frame rate, illustrated in Figure 3-42.

3.11 SUMMARY

The following conclusions on update rate seem appropriate:

With TV video systems refreshed at standard rates to combat flicker, frame rates between 0.23 and 24 frames/second do not differently affect

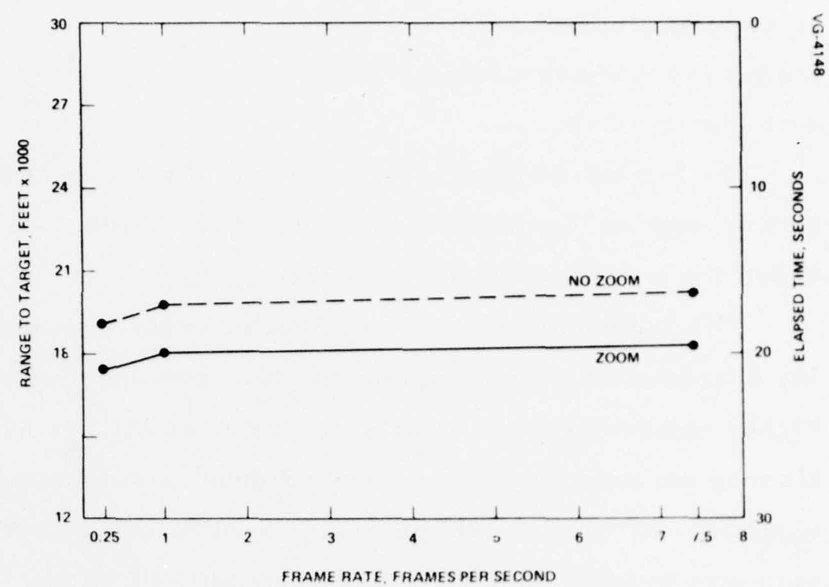


Figure 3-42. Zoom, frame rate interaction.

target recognition performance. However, initial delays in transmission of 1 to 2 frames may degrade performance at the lowest rates; this does not appear to be a significant consideration at update rates of 0.94 frame/second or greater. Target acquisition performance is not degraded by update rates as low as 0.23 when aided sensor modes are employed. With standard unaided 3-axis stabilized control modes, an update rate of at least 3.75 frames/second is required. When a precision designation or tracking task

is required, update rates of between 1.88 and 3.5 frames/second are adequate; minimal gains are found with higher rates.

The highest rate necessary in most of these cases is 3.75 frames/second. Lower rates will be adequate under the conditions described above.

With inner loop control functions on rapidly changing characteristics requiring a constant response, much higher update rates are required. Rates as high as 60 Hz may not produce performance as good as continuous updating, but in less critical tasks, a 20 frame/second rate may be adequate, since performance will be degraded by only 15 percent.

Finally, if good apparent motion is to be simulated with a TV display system, rates between 12 and 15 frames/second will generally be adequate.

When time compression techniques are employed to enhance apparent motion, short interframe intervals (<0.04 sec) produce higher probabilities of target detection, and will interact with frame duration.

Several display variables must be taken into consideration in the determination of update rate. Increasing update rates will increase display brightness; higher refresh rates will then be required to eliminate flicker. However, increased refresh rates will demand either a reduction in the number of picture elements (resolution) or an increase in bandwidth requirements. One alternative to higher refresh rates is a more spatially complex scanning method than progressive raster scanning or two-field interlace techniques. A second alternative is the use of long persistence phosphors, but as previously discussed, smearing effects may result with high update rates or rapidly moving images, possibly obscuring critical small details.

With LED displays, multiple images may result in situations where motion is to be simulated. The region of multiple images illustrated in Figure 3-17 should be avoided even if lower repetition rates are adequate to eliminate flicker.

In general, the task requirements, anticipation interval, and available response time should be the major considerations in determining minimum update rates. Increases beyond the necessary information requirements may be necessary to avoid flicker, multiple images, or jerky motion, but will entail costs in terms of bandwidth or resolution. All of these factors should

be simultaneously considered in the determination of optimal update rate.

4.0 ENVIRONMENTAL FACTORS IN THE DESIGN OF IMAGING SENSOR DISPLAYS

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4.1 INTRODUCTION

Operator visual task performance with an aircraft sensor system is influenced to a considerable extent by the exigencies of the flight environment. Environmental stressors such as acceleration, vibration, heat, noise, and oxygen deprivation can affect the display hardware, human operator, or both. For example, aircraft vibration may threaten the integrity of the display unit and/or may degrade operator visual task performance capabilities. Typically, technological advances lead to the development of hardware which can withstand anticipated operational stresses. Therefore it is often the limited capabilities and restrictions of the human operator that function to bound system performance.

The fact that human operator requirements may limit system output does not mean that system performance improvement is beyond the control of the hardware designer. On the contrary, alterations in system design can be used to compensate for environmental-stress-induced reductions in operator capabilities, and so maintain performance at acceptable levels. However, before such compensatory design can occur, the designer must understand the exact mechanisms by which the environmental stressors impact performance, because different design solutions are appropriate assuming different problem origins.

The purpose of this literature review section is to specify as precisely as possible the mechanisms by which selected environmental factors impact

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visual task performance. The following design requirements section builds upon this identification of causal mechanisms to suggest how environmentally-caused performance decrements can be reduced by design modifications.

The two environment factors chosen for consideration in this section are vibration and acceleration. These parameters were selected because they are unavoidable elements of the flight environment which may severely impact vision. Although it is difficult to eliminate the source of these phenomena, it is possible to lessen their impact on visual task performance by manipulation of display design parameters. Other environmental stressors such as noise, excessive heat or cold, and oxygen deprivation can be more readily eliminated at their source.

Various environmental stressors undoubtedly interact such that their combined effects cause greater performance decrements than would be anticipated by a summation of their separate effects. Unfortunately, little research exists on the simultaneous effects of multiple stressors, therefore only a few of the many possible interactions can be discussed in this report.

4.2 VIBRATION

4.2.1 Summary

The literature regarding the effects of vibration on human performance is reviewed in an attempt to identify the parameters likely to affect sensor-display operator target acquisition performance. Any targeting task may be conveniently considered as composed of three component tasks, each of which is potentially susceptible to vibration for different reasons: (a) a sensor input or visual perception task, (b) a central processing or decision making task, and (c) an output or motor task (which includes such behavior as tracking, cursor positioning, etc.). The effects of, and intervening mechanisms contributing to vibration impact on the first two tasks are of interest in the present report.

4.2.2 Introduction

Whether a sensor operator attempts to visually locate, identify, or classify a target on his display, the nature of the visual input received by the operator is critical for task performance. If critical scene information is lost between the real world and the display, or between the display and the observer's

percept of the world, task performance will be degraded. Under certain vibration conditions, the displacement of the visual image on the retina will result in visual blur and a concomitant loss of sensory information. Whether blur is interpreted from a display standpoint as producing reduced effective display resolution, or with reference to the operator as occasioning reduced visual acuity, the important consideration is that the reduction in quality of the visual stimulus information received by the operator is likely to hinder task performance.

Once a visual input is received by the operator, the nature of the task to be performed dictates the amount of central neural processing required for successful completion. Thus, for example, the level of decision processing required to determine if a perceived blob is a specific type of vehicle (target identification or classification) is presumably greater than that required to determine if a perceived blob is merely an object of interest requiring further examination (target detection). Central processes require that a certain amount of observer attention be directed toward their completion. Under certain conditions vibration may constitute a competing stimulus serving to direct operator attention away from necessary decision processes and may thus hinder performance accuracy or efficiency.

4.2.3 Background

Vibration is characterized by the "periodic displacement of a mass over time" (Hornick, 1973, p. 300). The parameters of vibration are frequency, amplitude (displacement), velocity, acceleration, and jolt. For a fixed frequency, the last three terms are successive derivatives of amplitude with respect to time (Morgan, Cook, Chapanis and Lund, 1963). Frequency, amplitude and acceleration, however, are the most often specified. Frequency is expressed as cycles per unit time, typically cycles per second or Hertz (Hz). Amplitude, one measure of vibration intensity or magnitude, is expressed in terms of displacement and usually refers to the maximum single or "half-wave" displacement from the null position. However, it is also quite common to find reference to the full-wave, "peak-to-peak" or "double amplitude." Maximum acceleration is also used as a measure of vibration intensity and is typically expressed in terms of gravitational units (g).

Vibration occurs in surface, air and/or space vehicles. For example, vibration occurs in reciprocating aircraft of all kinds, in turbine powered

aircraft when buffeting occurs, and especially in helicopters (Wulfeck, Weisz and Raben, 1958). The use of low-altitude, high-speed (LAHS) flight as a tactical penetration technique has increased the chances of pilot survivability but has also increased low frequency, high amplitude vibration exposure resulting from the relatively severe atmospheric turbulence encountered at low altitudes (Beaupeurt, Snyder, Brumaghim, and Kanpp, 1969; Holland, 1966). The helicopter vibration frequency spectrum ranges from about 3 to 110 Hz, with dominant frequencies occurring in the 10 to 30 Hz region. These predominant oscillations are associated with the rotor revolution rates. Harmonics of progressively milder intensity occur at higher frequencies, depending on structural characteristics (Schuett 1967).

Although vehicular vibrations can occur over a wide range of frequencies, human performance is most likely to be effected by whole body vibration in the frequency range of 1 to 30 Hz (Ketchel, Danaher, and Morrisey, 1969). Oscillation below 1 Hz is not usually referred to as vibration because at such frequencies, the whole body tends to follow the motion and the primary sensory stimulation is to the vestibular system (inner ear) causing motion sickness. Within the 1-30 Hz range, however, buffeting occurs in LAHS flight, the dominant helicopter main rotor frequencies occur, resonances of important body areas are found, and visual blur is reported. At frequencies above 30 Hz, it is relatively easy to protect the human body against vibrations by means of mechanical damping systems, and any such frequencies transmitted to the body are attenuated by the soft tissues (Coermann, 1962; Magid, Coermann, and Ziegenruecker, 1960; Morgan, Cook, Chapanis and Lund, 1963; Shoenberger and Harris, 1969).

Vibration can be sinusoidal, complex (consisting of two or more sine waves in combination), or random. Random vibration may be random with respect to either frequency or amplitude, or both. For example, given any particular frequency, the amplitude may change from one oscillation to the next, or amplitude may remain constant and frequency may vary. Most of the human vibration research conducted has been with sinusoidal vibration partially because it has proven difficult to correlate the body responses with random vibratory motion. In addition, because major performance effects may be due to discrete frequencies and amplitudes within a complex spectrum, it is practical to investigate uniaxial sinusoidal vibration (Clark, Lange and Coermann, 1962; Hornick, 1962). Information obtained under sinusoidal motion can then be used

to predict the performance effects of complex sinusoidal or random waveforms by decomposing them into their component sums of sine and cosine waves. This is convenient because the specific vibration spectrums of existing and future vehicles may vary due to vehicle propulsion system, size, structural characteristics, and speed envelope, while the human response to the basic vibration parameters can be expected to remain relatively constant (Hornick, 1973).

Another important parameter to consider when assessing the impact of vibration on man is the axis in which the oscillation occurs. Vibration of human subjects is usually described with reference to three orthogonal axes: $\pm g_z$, referring to the head-to-feet axis; $\pm g_x$, referring to the fore-aft axis; and $\pm g_y$ referring to the right-left, or lateral axis.

The majority of human vibration studies have been conducted with seated subjects experiencing g_z or "vertical" vibration. Studies investigating other postures and axes have shown that the vibration transmission of the human body and its resonant frequencies vary with changes in the body center of gravity and orientation relative to gravity and that performance effects determined with seated subjects and g_z vibration cannot be readily generalized to other postures and axes (Clark, Lange and Coermann, 1962; Coermann, 1962; Griffin, 1975; Morgan, Cook, Chapanis and Lund, 1963; Taub, 1964).

Vertical sinusoidal vibration may be easily quantified in terms of its frequency and intensity (amplitude or acceleration). Mathematically, for sinusoidal vibration, peak acceleration in g's is a function of the product of displacement amplitude (a) and the square of the frequency (f^2). Because human subjective and biodynamic response to and performance under vibration is frequently a function of both frequency and amplitude (Dennis, 1965; Ketchel, Danaher and Morrissey, 1969; Taub, 1964; Teare and Parks, 1963), one might be tempted to relate such effects to measures of acceleration, which are also a function of these two parameters. However, the nature of the human vibration response is such that acceleration alone fails to account for much of the observer variation in measures of performance and comfort, principally because different parts of the body have resonance peaks at different frequencies and transmission of vibration through the body varies (generally inversely) with the frequency (Coermann, 1962; Holland, 1966).

4.2.4 Target Acquisition Under Vibration

For a sensor operator to successfully acquire a displayed target, he must first be able to perceive

certain necessary scene information. Whole-body vibration may interfere with his ability to do so. This effect has been demonstrated both when the man is vibrated and the target is static (Lange and Coermann, 1962; Mozell and White, 1958), and when the operator and target are vibrated simultaneously (Taub, 1964; Teare and Parks, 1963). Some of the tasks used to assess the effects of vibration on visual performance have been digit reading, dial reading, and standard visual acuity tasks such as Landolt C detection or Snellen chart reading.

It is difficult to draw reliable generalizations from the literature because of the diversity of experimental tasks employed, the differing ambient illumination and contrast conditions existing, the use or non-use of seat belts and seat cushions (which modify the transmission of vibration input to the subject), the differing characteristics of the usually small subject populations, the fidelity of the vibration platform, and the vibration or non-vibration of the display. When researchers use constant amplitudes with varying frequencies, it is difficult to determine whether effects found to increase with higher frequencies are in fact related to frequency or intensity. On the other hand, when constant g levels are used, amplitudes become smaller for higher frequencies. In addition, subjects vary in their subjective and physical responses to vibration, the transmissibility of vibration to the subjects head, and the performance decrements experienced under vibration (Beaupeurt, Snyder, Brumaghim and Knapp, 1969; Coermann, 1962; Coermann, Magid and Lange, 1962; Griffin, 1975; Parks, 1962; Teare and Parks, 1963).

Results from most studies have been presented with reference to two parameters: (a) the frequency of the forcing vibration and (b) the displacement amplitude or acceleration of the vibration platform (Dennis, 1965). Unfortunately, however, acuity scores related only to table movement do not adequately address the causal relationships because such factors as table vibration fidelity, the degree of coupling between the subject and the vibration source, and inter-subject differences, will modify the vibration actually impinging upon the subject and the subject's eye. The vibration transmitted to the subject's body determines the performance decrement due to the distracting effects of unpleasant sensations caused by vibration-induced resonance of body structures, and the vibration transmitted to the subject's head or eyes determines the performance decrement caused by image displacement or blur.

Image blur under vibration results when the movement of the image on the retina is too rapid for clear perception. Such blur could result simply from the relative displacement of the display and the observer's eyes or could be further complicated by resonances and deformation of the eyeball itself. By integrating results obtained in studies reporting the physical and performance effects of vibration, it is possible to provide some tentative evidence that visual task degradation occurring under vibration is partially due to visual blur.

None of the studies reviewed reported visual performance decrements below 4 Hz. Significantly, it is also reported that at frequencies up to approximately 2.5 to 4 Hz, the eye is capable of making "following" or compensatory tracking movements in order to maintain fixation of a vibrating target (Guignard and King, 1972). Guignard and Irving (1962) report that the amplitude of the eye movements falls to less than 50 percent of the input amplitude at frequencies above 2.5 Hz. These authors, investigating vibration at $\pm 0.25\ g_z$ at frequencies from 2.4 to 9.5 Hz, also found decrements on a visual search task to be greatest between 3 and 5 Hz and attributed this to a breakdown of compensatory eye movements as frequency increased, and to whole-body resonance effects that were greatest in the same band of frequencies.

Above approximately 5 Hz, the eye can no longer perfectly follow the motion of the oscillating target, and performance is found to decrease both with increasing vibration frequency and amplitude (Lange and Coermann, 1962; Mozell and White, 1958; Rubenstein and Taub, 1967; Taub, 1964; Teare and Parks, 1963). Numerous authors have interpreted their results as being due to the blur caused by displacement of the image relative to the eye (Lange and Coermann, 1962; Teare and Parks, 1963) and by resonance of the eyeball (Dennis, 1965), further results from studies assessing the subjectively-reported physical effects of vibration specifically reported blurring of vision between 8 and 28 Hz (Chaney, 1964; Parks and Snyder, 1961).

While the previously-cited studies tend to support the conclusion that degradation in visual performance occurs due to visual blur which increases with increasing vibration intensity and amplitude, a more exact statement as to the nature of this effect and

the relative contribution of frequency and amplitude is not possible, because of the differing methodologies of the studies involved, and because the reported amplitudes and accelerations were measured at the vibration table and not at the subject's eye.

The crucial vibration to consider when evaluating the effects of vibration on visual blur is that affecting the subject's eye. The vibration intensity transmitted to the eye of a seated subject is dependent upon the vibration frequency, the subject's posture, the seat cushions and restraints, etc. However, the following results are typical of those reported: From 0 - 1 Hz, head vibration amplitude is near that of the seat. Head amplitude increases with frequency up to a peak at about 3-6 Hz where maximum head vibration (resonant frequency) occurs and the head amplitude is 150 - 300 percent of the seat amplitude. Then as frequency increases, head vibration decreases and at 10 Hz head and seat amplitude are again equal. Seat-head transmission then decreases progressively at higher frequencies until it reaches only 10 percent at 70 Hz. There are one or two secondary resonances which also occur, apparently due to a shoulder-head transmission resonance at 20-25 Hz (Dieckmann, 1958).

One of the few studies which has investigated visual task performance under vibration in terms of amplitudes measured at the subject's head was conducted by Dennis (1965). He looked at the effects of whole-body vibration upon a digit reading task at two levels of peak-to-peak acceleration over a range of 5 to 37 Hz. A peak-to-peak acceleration of 1/2 g was labeled Light (L), and a peak-to-peak acceleration of 1 g was referred to as Heavy (H). Movement of the head showed progressive attenuation as frequency of vibration was increased.

Dennis (1965) found that under heavy vibration, reading error per unit amplitude of head movement increased from 7 to 37 Hz, thus confirming that above some minimum intensity level (which is in turn frequency-dependent), visual task performance degradation is inversely proportional to frequency.

Dennis (1965) also noted that equivalent levels of impairment were produced by progressively decreasing amplitudes of head movement as frequency increased. He pointed out that at the higher frequencies (27 to 37 Hz) relative movement between the head and visual object was a fraction of the size of the smallest foveal cone but visual performance still showed significant deterioration. He interpreted this

later effect with reference to Coermann's theory of a resonating structure existing between the skull and the retina and in terms of Guignard's suggestion that decrement found in the upper frequencies is due to resonance of the facial tissue impinging on the eyeball, both of which presumably cause visual blur. Thus, it appears that the visual blur phenomenon may be caused by slightly different physical and mechanical phenomena at different frequencies, being predominately a function of relative displacement of the eye and displayed information at some frequencies, and a function of eyeball and facial tissue resonance and deformation at others.

It has been suggested herein that degradation of visual task performance occurring with increasing vibration frequency and amplitude within the frequency range of 4 and 30 Hz is primarily due to the disruption of target perception due to visual blur. What is needed before a determination of the quantitative relationship between vibration frequency/intensity and visual performance can be made is a study in which performance is related to directly measured observer eye movements, rather than table vibration or even head motion.

It has also been suggested that aside from mechanically disrupting scene perception by causing visual blur, vibration may also cause additional visual performance decrement by disturbing central decision processes. Direct evidence for this conclusion is sketchy but tentative support is provided by consideration of related investigations.

It was stated earlier that the human body responds to vibration like a complex mechanical system, a "complicated system of masses, elasticities and viscous dampers each connected to the others" (Coermann, 1962, p. 227). Several studies have shown that vibratory forces produce perceptible feelings of pain, annoyance or fatigue (Chaney, 1964; Morgan, Cook, Chapanis and Lund, 1963; Parks and Snyder, 1961). In fact, the highest sensitivity in terms of physiological and psychological effects appears to be to accelerations in the frequency range of 1-30 Hz, precisely the region where performance decrements occur.

Several investigators have suggested that the presence of pain and fatigue may degrade performance by diverting operator attention necessary for effective information processing. Thus, for example,

Coermann, Magid and Lange (1962) noted that there is

> "... a profuse complex of receptors distributed throughout all parts of the body [that] collectively represents general somesthetic sensibility. This group includes the receptors of touch, pressure, proprioception, pain and visceral sense. All of these receptors are susceptible to displacement of adjacent tissue and can, therefore, be stimulated by vibration... These considerations explain why the mechanical resonances within the body are so obviously reflected in the performance of human subjects under vibration. The stimulation of the receptors in the body withdraws the attention of the subject from his task, increasing his error," (p. 323).

Similarly Semple (et al, 1971) concludes that "cerebral-intellectual impairment may result from the withdrawal of the observer's attention from his task due to the physiological and psychological stress induced by vibration," (p. 512).

More concrete evidence for the existence of a physiological or psychological based "distraction" factor comes from two sources. First, most investigators have found that vibration of the subject is more detrimental to visual acuity than vibration of the viewed object (Crook, 1950; Ketchel, Danaher and Morrissey, 1969). Since displacement of the target relative to the observer's eye is likely to be greatest when the display alone is vibrated, the fact that performance is worse when the man is vibrated lends some support to the "distraction" hypothesis, especially at the lower frequencies where eyeball resonance does not occur. Substantial support is added by studies which report that performance degradation effects continue after cessation of vibration; this effect cannot be the product of blur phenomena (Coermann, Magid, and Lange, 1962; Hornick, 1961).

To separate the degradation in performance resulting from "blur" and "distraction," a study is needed in which the visual task performance of a vibrating subject, assessed with respect to image displacement on the retina, is compared to the performance of a vibrating subject who views a target image which has been stabilized on the retina. Image stabilization should be accomplished by slaving a display to subject eye movements under vibration. (Note that small image displacements would need to be transmitted to the retina in order to prevent the stabilized image from disappearing due to adaptation.) Any performance differences found between the two conditions would likely be the result of factors other than blur.

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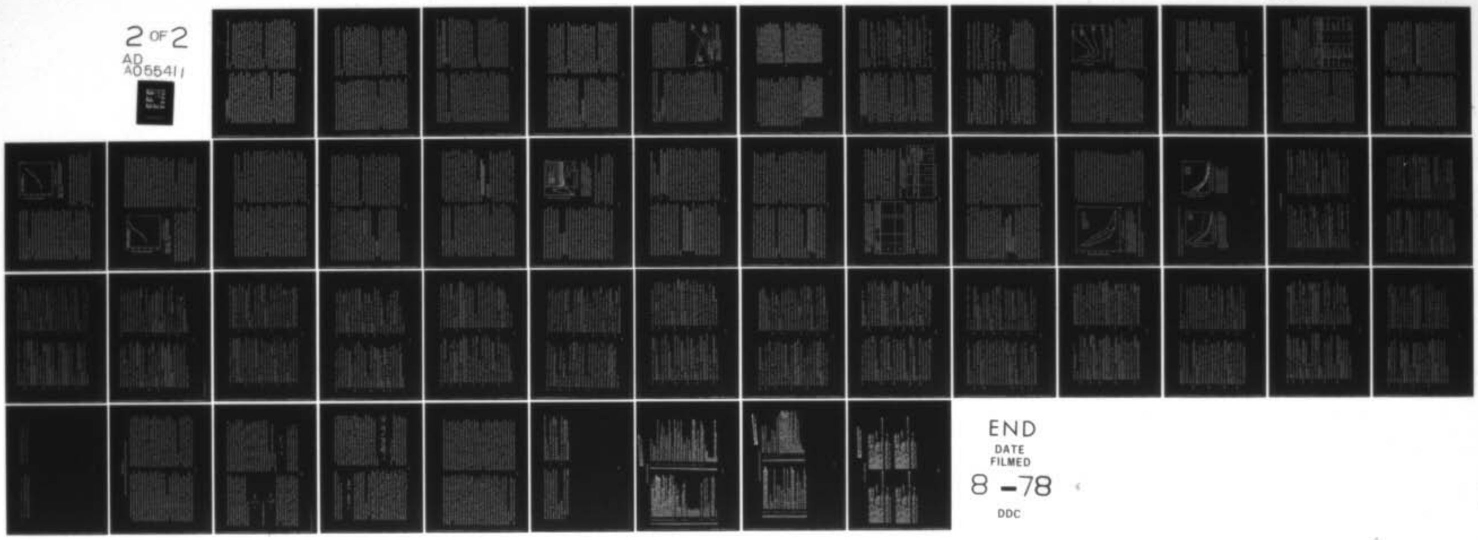

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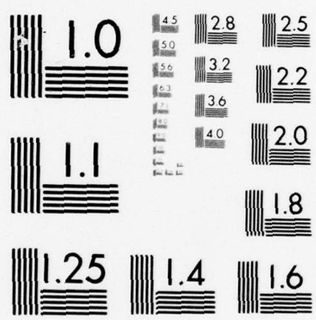
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4.2.5 Recommendations

Research cited above indicates that vibration of the operator is more detrimental to visual acuity than vibration of the target. Thus, attenuation efforts should focus on isolation of the subject as a primary goal with isolation of the viewed object as an important but secondary consideration. A certain amount of vibration isolation is possible through careful design of seat cushions and restraint devices. However, while cushions are generally very effective in damping higher frequencies, they are generally ineffectual in the human resonance range (4-6 Hz); Morgan, Cook, Chapanis and Lund, 1963. It has also been suggested that, considering the large inter-individual differences in reaction to vibration, it might be beneficial to select persons for a task according to their sensitivity to vibration (Griffin, 1975).

Several studies have demonstrated that the visual effects of vibration on performance may be reduced by proper design of displayed matter. For example, some studies have shown that small increases in the size of characters of reading material can offset the difficulty presented by vibration (O'Hanlon and Griffin, 1971; Teare and Parks, 1963). More specifically, Teare and Parks (1963) found no decrement under vibration for digits subtending more than 12 minutes of arc.

One study evaluated the effects of helicopter vibration on operator target recognition performance (Carel, Herman, and Hershberger, 1976). This tactical target recognition study compared performance under conditions of vibration typical in a UH-1N helicopter with performance in the absence of vibration. Both the observer and the panel mounted display were vibrated. The results showed that a 35 percent increase in target subtense was required to maintain performance levels equivalent to those obtained under static conditions.

A correction factor applied to adjust one set of data (for example, static performance data) to determine performance under another set of conditions (for example, vibration) is often called a "field factor." The vibration field factor of 35 percent for tactical target recognition established in this experimental investigation was slightly less than that established for maintaining alphanumeric (displayed map information) legibility under similar vibration conditions (41.89 percent, as determined by Carel, McGrath, Hershberger, and Herman, 1974). This

difference was interpreted as resulting from the differing level of detail discrimination required by the two tasks. In the case of alphanumeric legibility, internal structural details are of primary importance for allowing discrimination between symbols (for example, to differentiate the symbols R, B, and P). On the other hand, for a target recognition task external target shape contours aid in target recognition even when internal modulation cues are degraded or absent. It was speculated that the slightly greater legibility decrement observed under vibration for the alphanumeric task was attributable to the finer level of structural discrimination required, as it seemed plausible that vibration would degrade internal structural detail discrimination to a greater extent than overall target contour recognition.

If blur caused by movement of a vibrating image on the retina is indeed an important reason for visual task degradation, then a collimated display should present a possible solution. The argument for the beneficial effects of a collimated display in a vibration environment is based on the fact that, for a given linear displacement of the eye or the displayed image, the relative angular displacement between the two is reduced as the distance between them increases. Collimating a display produces a virtual image of that display at infinity which should produce a stationary retinal image and a consequent enhancement of visual acuity.

Two studies were found which examined the effects of collimating a display under vibration. One study (Craiger, 1966) evaluated display collimation for frequencies up to 5 Hz and amplitudes up to ±0.7 inch. However, only one subject was used and the experimental conditions were poorly described. The subject's task was to estimate the reading errors for various size numeral scales both with and without collimation. The estimated reading errors were reduced to equivalent angles subtended at the eye and it was estimated that compared to no collimation an approximate eight time reduction in required scale size was obtained when display collimation was employed.

A second study (Wilson, 1974) evaluated the effects of display collimation on visual task performance using a two-axis tracking task. Display collimation resulted in 12.6 and 3.5 percent performance improvement, compared to no collimation, for vibration frequencies of 5 and 10 Hz.

It is also reasonable to assume that helmet mounted displays might be effective in reducing the degrading effects of vibration. The amount of

vibration at the display would be reduced by the attenuation that takes place in the seat cushion and operator's body. Thus, the relative displacement between the operator's eye and displayed image would be minimized.

In most of the studies investigating the effects of vibration on visual task performance, other factors such as display contrast, ambient illumination, noise level, etc., were controlled but not manipulated. However, it is desirable to have information on the interaction of vibration parameters with other environmental and display parameters. Some tentative results are available from a study by Carel, McGrath, Hershberger, and Herman, 1974. Investigating the legibility of alphanumeric symbols under no vibration and the vibration spectrum of a UH-1N helicopter, these investigators found statistically significant interactions between vibration and certain map display system paramters. Specifically, vibration was found to interact with display contrast/luminance conditions and clutter such that the percent increase in visual angle required for maintaining readability under vibration was most pronounced for the 6.0/0.1 fL and 0.8/0.1 fL contrast/luminance conditions and greater for the high-clutter display condition. Visual performance can be at least partially protected under vibration by proper consideration of display design variables.

4.3 MAINTAINING VISUAL CAPABILITIES UNDER VIBRATION STRESS: DESIGN RECOMMENDATIONS

Considerable evidence has been presented to support the conclusion that vibration degrades visual task performance. Before rational design solutions can be found for this problem, however, two important steps must be taken: (1) the specific mechanisms by which vibration effects performance must be outlined, because different solutions are appropriate assuming different problem origins and (2) the identified cause-and-effect functions must be quantified.

Integration of the existing research in the foregoing review section led to the identification of two mechanisms by which vibration impacts visual task performance: (1) by causing visual blur of the perceived image and (2) by causing withdrawal of observational or decision processes by evoking physiologically-based subjectively unpleasant sensations. Unfortunately the data which presently exists does not allow objective quantification of these functions. Nevertheless, in this section, a "first cut" at the problem will be made. In reference to the blur

phenomenon, a model is developed detailing a procedure for relating aircraft vibration spectrums to design-relevant visual parameters, namely resolution and modulation. In reference to the "distraction" effect, a representative operator subjective vibration tolerance curve is presented to indicate the frequencies and amplitudes at which this effect would be most likely to occur. Although the blur and distraction factors will be discussed separately in this section, one should bear in mind that either or both of these effects may be operative in any specific vibration situation.

4.3.1 Vibration Induced Blur

The primary cause of vibration-induced blur is the relative displacement which occurs between an observer's eye and a displayed image when such displacement is at rates too rapid for the eye to follow. Because the eye integrates visual information perceived over a period of approximately 100 milliseconds, what is seen is essentially a "composite" image simultaneously depicting the target in its successive positions over the 100 millisecond period. Thus transmission of each single point of displayed information is distorted by the vibration so that it is perceived by the human operator as a blur rather than as a point. This phenomenon is similar to point spread occurring during sensor image formation, where the signal representing each real world "object point" experiences a distortion while proceeding through the system such that each corresponding displayed "image point" is actually composed of a series of blurs.

Based on the premise that vibration can be viewed as producing a modification of the original system point spread function, a model has been developed whereby the effects of any given aircraft vibration spectrum on human operator performance can be represented as a modification in the system modulation response curve. By comparing the original and modified system MTFs with the operator visual demand function, the effective reduction in system resolution occurring under vibration is ultimately determinable.

The logical development of the model is described in the following paragraphs. The actual mathematical calculations, which are referenced in the theoretical discussion, are presented in Section 4.3.3. Because of the dearth of data relating input vibration parameters to observed operator eye movements, some of the model parameter values are not well known at this

point. However, as such information becomes available it may be incorporated into the present proposed framework.

4.3.2 Theoretical Model

In an operational aircraft, the relative motion between the observer's eye and the display is a function of several critical factors. The vibration source, or forcing function, is determined by such factors as the rotation rate of the main helicopter rotor or the air turbulence encountered in Low Altitude High Speed flight in fixed-wing aircraft. The transmission of the input vibration frequencies and amplitudes to the operator's eye is affected, in turn, by such factors as the type of seat cushioning, the nature of the restraint system, and operator body inertia, which includes effects of damping and body resonances. The transmission of the input vibration to the display is a function of the nature of the display mounting, display damping and structural resonances. However, it is possible to analyze operator eye and display motions, taking into account the above factors, to determine relative eye-image motion (see steps 1-4 of mathematical model).

Given the relative eye-image movement information and the original system point spread function, one can (through the calculations described in steps 5-10 of the mathematical model) determine the effective system point spread function in the presense of vibration. Through further analysis (steps 11-13), it is then possible to express the modified point spread function as a system modulation response curve. Comparing the new response curve to that existing without vibration, and noting the relationship between each of these curves and the operator's visual demand function (see Figure 4-1), allows a determination of the effective reduction in resolution occurring under vibration.

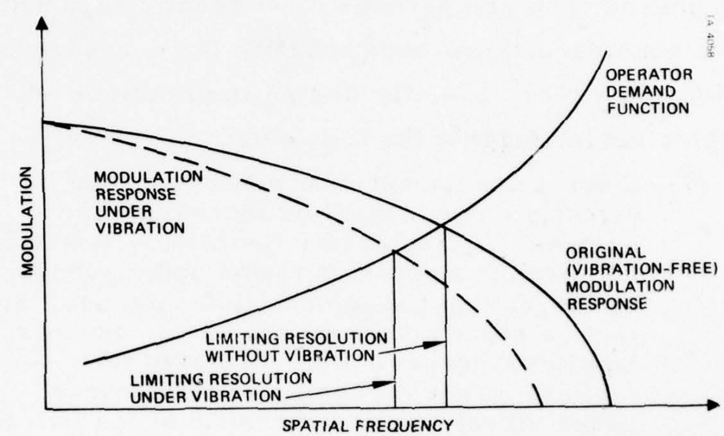

Figure 4-1. Hypothetical modification of system modulation transfer function (MTF) under vibration.

In the proposed model, the effect of vibration on vision is interpreted from a display standpoint; that is, with vibration seen as producing reduced effective display resolution. It is also possible to view the effects of vibration from the operator's standpoint, as decreasing visual acuity. Since the vibration modified system modulation transfer function (MTF) can be calculated, whereas the operator vibration modified psychophysical demand function would need to be empirically assessed, the former approach was selected for mathematical modeling. However, the design implications of the blur *phenomenon* are perhaps most readily apparent in the consideration of compensation for decreased acuity. In either case, the design implications of the blur model suggest the following:

(1) Since a decrement in visual acuity can be directly compensated by increasing the subtense of displayed information, it should be possible to protect vision under vibration by increasing the information subtense. In fact, a study conducted by Carel, Herman, and Hershberger (1976) indicated that tactical target recognition performance under vibration charactersitic of the UH-1N helicopter could be maintained equivalent to static levels with a 35 percent increase in target subtense. In a previous study (Carel, McGrath, Hershberger, and Herman, 1974), alphanumeric legibility was maintained at static performance levels under the same vibration spectrum with a 42 percent increase in symbol subtense. The slight discrepancy between the required increases in the two situations was attributed to the higher level of detail discrimination required by the alphanumeric task. However, the important fact is that vision under vibration can be protected by increasing the subtense of displayed information.

(2) Because visual acuity is a function of visual adaptation level and image contrast, vision under vibration can be protected by increasing display brightness and/or contrast. However, a reduction in display dynamic range typically accompanies such a 'hardening' of the image. Because of this trade off, it may be that different solutions are optimum depending on the nature of the vibration source. Thus, in a helicopter, where vibration is unavoidable, the advantages of the hardened display image may override the loss of dynamic range. However, in fixed wing aircraft, where vibration is experienced only intermittently depending upon atmospheric and flight conditions, it may be desirable to provide a selectable hardened display mode so that maximum dynamic range can still be available in the absence of vibration.

4.3.3 Mathematical Model: Effect of Vibration on Display Point Spread Function and Resolution

1) Characterize the translational vibration signal by its power spectral densities $V_\ell(f)$ and $V_v(f)$ in the lateral and vertical axes respectively.

2) Assume translational motion transfer functions $H_{b\ell}(f)$ and $H_{bv}(f)$, respectively, in the lateral and vertical axes, between airframe motion and eyeball translation motion (includes effects of seat mounting, seat cushioning, and body inertia, damping, and resonances).

3) Assume translational motion transfer functions $H_{d\ell}(f)$ and $H_{dv}(f)$ in the lateral and vertical axes, *respectively*, between airframe motion and display surface translational motion (includes effects of display inertia, damping, and resonances, and shock mounting).

4) The effective transfer functions for relative motion are $H_{d\ell}(f)-H_{b\ell}(f)$ and $H_{dv}(f)-H_{bv}(f)$ respectively.

5) The eye will track low temporal frequency relative motions and automatically compensate for them in the perception process. The upper limit of this compensation capability is between 5 and 10 Hz. Thus the compensation process in the eye can be modelled as a pair of high pass filters with transfer functions, $H_{e\ell}(f)$ and $H_{ev}(f)$ in the lateral and vertical axes, respectively, which eliminate the lowest frequency components of the relative motion waveform.

6) The power spectral densities of relative eyeball/display motions U_ℓ and U_v are

$$E_\ell(f) = V_\ell(f)\,|H_{e\ell}(f)|^2\,|H_{d\ell}(f) - H_{b\ell}(f)|^2 \text{ and}$$

$$E_v(f) = V_v(f)\,|H_{ev}(f)|^2\,|H_{dv}(f) - H_{bv}(f)|^2.$$

7) Assume the relative vibrations in each axis are uncorrelated Gaussian random processes with zero mean. They are therefore characterized by their RMS values σ_ℓ and σ_v respectively.

8) $\sigma_\ell = \left(E\left[u_\ell^2\right]\right)^{1/2};\ \sigma_v = \left(E\left[u_v^2\right]\right)^{1/2};$

$$E\left[u_\ell^2\right] = R_\ell(o) = \int_{-\infty}^{\infty} E_\ell(f)\,df;\ E\left[u_v^2\right] = R_v(0) = \int_{-\infty}^{\infty} E_v(f)df$$

9) Let the lateral and vertical point spread functions (PSF) in the absence of vibration be m (x) and $m_v(y)$ respectively.

10) Then the lateral and vertical optical transfer functions (OTF) without vibration are

$$M_\ell(f) = \int_{-\infty}^{\infty} m_\ell(x)e^{-j2\pi fx}dx \text{ and } M_v(f) = \int_{-\infty}^{\infty} m_v(y)e^{-j2\pi fy}dy$$

respectively. The modulation transfer

functions (MTF) are simply $|M_\ell(f)|$ and $|M_v(f)|$ respectively.

11) Let the lateral and vertical point spread functions under vibration be $m_{\ell v}(x)$ and $m_{vv}(y)$ respectively. Then $m_{\ell v}(x)=m_\ell(x)(*)p_\ell(x)=\int_{-\infty}^{\infty} m\,(s)p_\ell(x-s)ds$, where (*) denotes the convolution operation and $p_\ell(x)=\frac{1}{\sqrt{2\pi\sigma}}e^{-x^2/2\ell^2}$ is the probability density function (PDF) of the lateral relative vibration. Similarly, $m_{vv}(y)=m_v(y)(*)p_v(y)=\int_{-\infty}^{\infty} m_v(s)p_v(y-s)ds$ and $p_v(y)=\frac{1}{\sqrt{2\pi\sigma}}e^{-y^2/2v^2}$.

12) The OTF under vibration are then $M_{\ell v}(f)=\int_{-\infty}^{\infty} m_{\ell v}(x)e^{-j2\pi fx}dx$ and $M_{vv}(f)=\int_{-\infty}^{\infty} m_{vv}(y)e^{-j2\pi fy}dy$. The corresponding MTFs are $|M_{\ell v}(f)|$ and $|M_{vv}(f)|$ respectively.

13) The MTF effect can be studied directly in the spatial frequency domain. Because convolution in space is equivalent to multiplication in spatial frequency, and because $m_{\ell v}(x)=m_\ell(x)(*)p_\ell(x)$, we have $M_{\ell v}(f)=M_\ell(f)P_\ell(f)$, where $P_\ell(f)=P_\ell(x)e^{-j\ fx}dx$ and $|M_{\ell v}(f)|=|M_\ell(f)|\ |P_\ell(f)|$. Similarly, because $m_{vv}(y)=m_v(y)(*)P_v(y)$, we have $M_{vv}(f)=M_v(f)P_v(f)$, where $P_v(f)=\int_{-\infty}^{\infty} p_v(y)e^{-j2\pi fy}dy$ and $|M_{vv}(f)|=|M_v(f)|\ |P_v(f)|$.

14) Because the vibration PDF are Gaussian, their Fourier transforms $P_\ell(f)$ and $P_v(f)$ are also Gaussian. We have $P_\ell(f)=\frac{1}{\sqrt{2\pi\sigma_{f\ell}}}e^{-f^2/2\sigma_{f\ell}^2}$, where $\sigma_{f\ell}=\frac{1}{\sqrt{2\pi\sigma_\ell}}$, and $P_v(f)=\frac{1}{\sqrt{2\pi\sigma_{fv}}}e^{-f^2/2\sigma_{fv}^2}$, where $\sigma_{fv}=\frac{1}{\sqrt{2\pi\sigma_v}}$.

4.3.4 Vibration Induced Distraction

There is some evidence to support the conclusion that aside from mechanically disrupting scene perception by causing visual blur, vibration may also occasion additional visual performance decrement by withdrawing observer attention from task performance because of physiologically or psychologically induced stress (see Literature Review section). The best available information concerning the vibration

frequencies and amplitudes at which such a distraction effect would be most likely to occur is provided by the human Subjective Tolerance curves. Such curves have been obtained by exposing subjects to gradually increasing vertical vibration intensities at successive frequencies, and having them report the acceleration levels at which they judged the vibration amplitudes to be "perceptible", "mildy annoying", "extremely annoying", and "alarming". See Figure 4-2. Presumably the greatest distraction would occur at levels where the vibration is perceived as being most threatening.

The data from such studies is not entirely consistent for several reasons. First, there is the problem that the labels may be defined and/or interpreted in several ways. Also, since individuals vary in their physiological as well as psychological susceptibility to vibration, they are apt to apply the labels differently. Further, situational variables such as motivation may effect the determination. In general, however, the results of such studies have shown that the higher the G level, the more severe the attached label (Chaney, 1964; Goldman, 1948; Parks and Snyder, 1961). In addition, the curves reveal that human

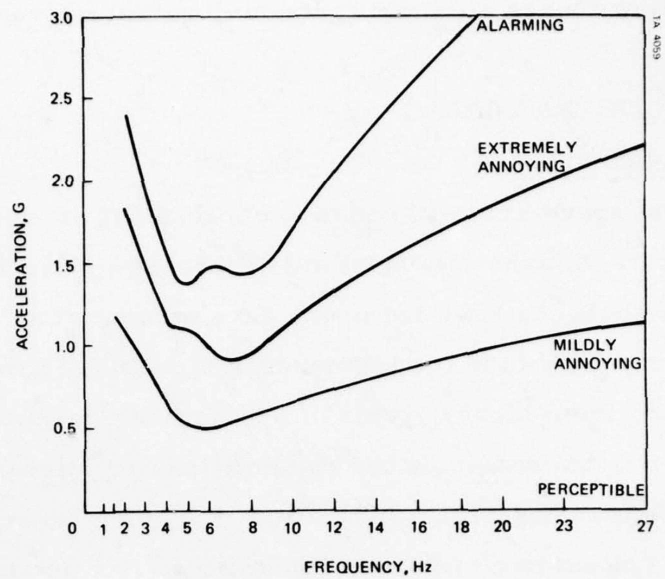

Figure 4-2. Subjective human vibration response curves (Chaney, 1964)

subjective tolerance is lowest to vertical vibration frequencies in the range of 4 to 10 Hz than to frequencies outside this range (Beaupeurt, Snyder, Brumayhim, and Knapp, 1969; Chaney, 1964; Goldman, 1948; Parks and Snyder, 1961). The implication is that the vision protection techniques outlined in the previous section are probably most crucial for vibration environments in which the predominant frequencies and amplitudes coincide with those

corresponding to minimum human vibration tolerance levels.

4.4 ACCELERATION

4.4.1 Summary

The speed and performance capabilities of modern military airplanes are constantly increasing. Technological advances have led to the development of aircraft which can withstand the tremendous structural strains resulting from higher levels of accelerative force. Thus, it is increasingly the capabilities and tolerances of the human operator which limit reconnaissance or strike system performance. Specifically, in an acceleration environment, a sensor operator's task performance is likely to be handicapped by disturbances of vision and consciousness. In this section, the physiological and psychological mechanisms mediating the effects of acceleration on vision will be discussed. The primary conclusion is that acceleration affects vision by causing retinal hypoxia (shortage of oxygen), which in turn results in an upward shift of absolute visual threshold (i. e., a decrease in visual sensitivity). Some evidence that blurring or loss of visual acuity may also result from acceleration-induced mechanical interference with the image producing properties of the eye, is also presented. In addition, the psychological impact of acceleration on performance is considered.

4.4.2 Introduction

Acceleration refers to a rate of change of motion, and occurs as a result of change in the speed or direction of a moving object. Linear acceleration is said to occur when the speed of an object increases or decreases but the direction of motion remains unchanged. Angular or radial acceleration occurs when the direction of object motion changes while speed remains constant, as when an aircraft executes a turn.

Acceleration acting on a mass produces a force which either causes the mass to move with constantly increasing velocity, or to deform if it is immovable. Similarly, the gravitational force resulting from the attraction between masses, affects objects near the surface of the earth, defining the weight of supported masses and causing unsupported masses to fall with a well defined acceleration "g";

$$g = 981 \text{ cm/sec}^2 \circ 32.2 \text{ ft/sec}^2.$$

This gravitational constant "g" is one accepted unit of measurement of acceleration. However, from the biological standpoint, it is the apparent weight caused by acceleration, and not the physical rate of change of velocity, which determines the human response. Apparent weight is caused by a reactive force resulting from the inertia of the body. This force is proportional to the mass of the body and the magnitude of the acceleration, and acts in a direction opposite to the acceleration. The symbol G has been adopted by many researchers to refer to a ratio which expresses weight (inertial force) as well as acceleration, in multiples of normal gravitational (1G) weight and acceleration. The G symbol will be used as the unit of acceleration in the present report. Though dimensionless, it can be treated as a vector.

The effect of acceleration on man depends not only upon its absolute magnitude, but also on several other factors including direction of application with respect to the body axes, onset or rise rate, duration, the use of protective devices by the operator, individual differences in physiological response, and the display and environmental conditions with which it interacts. The most important consideration appears to be direction of application. In order to provide a background for the succeeding discussion, a brief review of acceleration axis and duration terminology follows.

4.4.3 Acceleration: Axis of Application

The human physiological response to acceleration differs depending on the relationship between the accelerative force and the axis of the body. The following conventions have been adopted to express the directional quality of acceleration:

Linear motion	Direction of inertial (G) force	Physiological Symbols	Local descriptive terminology
Forward	Backward (chest to back)	$+G_x$	eyeballs in
Backward	Forward (back to chest)	$-G_x$	eyeballs out
Upward	Downward (head to foot)	$+G_z$	eyeballs down
Downward	Upward (foot to head)	$-G_z$	eyeballs up
Right	Left (right to left)	$+G_y$	eyeballs left
Left	Right (left to right)	$-G_y$	eyeballs right

A distinction is made between longitudinal and transverse G loads, the first acting parallel to the long (longitudinal) axis of the body, the latter acting perpendicular to this axis. Sometimes a further distinction is drawn between a narrower definition of transverse G (which is then limited to refer to chest-to-back and back-to-chest G_x acceleration only) and lateral (left-to-right, right-to-left) G_y.

In an aircraft environment, the G force impinging on an operator is a vector resultant of the accelerative force due to gravity and that due to a change in aircraft speed or direction. The effective axis of acceleration does not usually fall in one orthogonal axis but rather occurs as a vector with components of each axis. Typically, vectors experienced in aircraft are combinations of G_x and G_z, with minor components of G_y. For example, a predominant positive G_z component (1G) is experienced when the aircraft is flying straight and level with constant speed, during inside loop maneuvers, when pulling out of a dive, and in turns, where the pilot is pushed into his seat. A significant negative G_z component is experienced during entry into dives and in the outside loop maneuver.

4.4.4 Acceleration Duration and Rise Rate

The human physiological response to acceleration also varies in response to the acceleration rise time and duration. Typically rise rates are expressed as G's/sec and a useful time distinction is drawn between abrupt (0-2 sec.), brief (2.1-10 sec.), long term (10.1-60 sec.) and prolonged (longer than one minute) acceleration (Gauer and Zuidema, 1961). Accelerative forces in aircraft typically do not exceed one or two minutes.

4.4.5 Acceleration-Induced Visual Threshold Shift

Centrifuge research has demonstrated that acceleration can affect vision, causing increased absolute intensity (White, 1960) and differential visual thresholds (Braunstein and White, 1962), reduced visual acuity (Warwick and Lund, 1946; White and Riley, 1958; White and Jorve, 1956; White and Felder, 1958), narrowing of the visual field (Hallenbeck, 1946), grayout (loss of peripheral vision), and blackout (loss of foveal as well as peripheral vision while still retaining consciousness (Cochran, Gard and Norsworthy, 1954). Integration of the existing literature suggests that this entire series of visual disturbances can be understood

with reference to a common underlying mechanism: displacement of the visual threshold. This threshold displacement can, in turn, be traced to a specifiable origin — retinal hypoxia.

Evidence from several sources confirms the existence of an absolute visual threshold shift under acceleration and provides support for the interpretation of several observed visual symptoms in terms of such a decrease in visual sensitivity. White (1960) demonstrated a systematic increase in the absolute thresholds of foveal and peripheral vision with increasing acceleration under moderate magnitudes of $+G_z$ acceleration (maximum acceleration = 4G; acceleration onset rate = 1G/1.5 sec). The procedure employed involved a determination of both ascending and descending thresholds for detection of a 1/5 second duration 3° test light. The results of this investigation are presented in Figures 4-3 and 4-4.

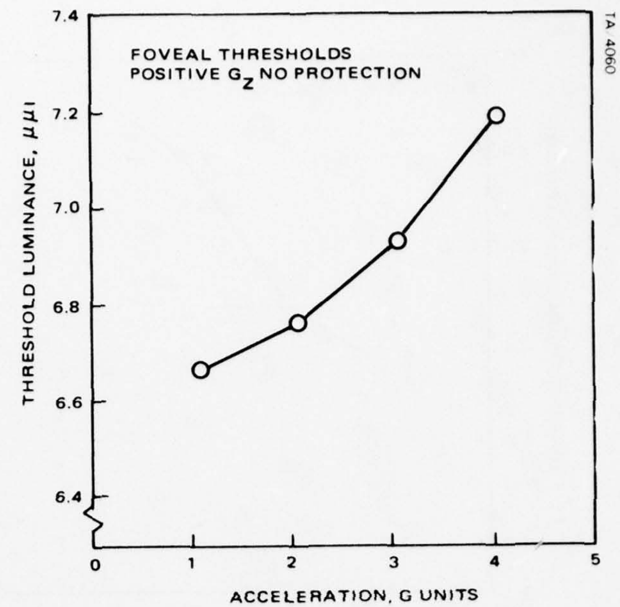

Figure 4-3. Threshold of foveal vision after +1 to +4 G_z acceleration (After White, 1960).

With higher levels of $+G_z$ acceleration than those investigated by White, grayout and blackout result. However, the fact that the G levels at which grayout and blackout occur vary, depending on the intensity and chromaticity of the test lights (Brown and Burke, 1957; Howard and Byford, 1956), indicates that these phenomenon do not denote absolute visual function failure, but rather are the result of a threshold shift.

Other investigators have reported increases in differential (contrast) thresholds (Braunstein and White, 1962), decreases in visual acuity (White and Felder, 1958), and increases in instrument (dial) reading errors

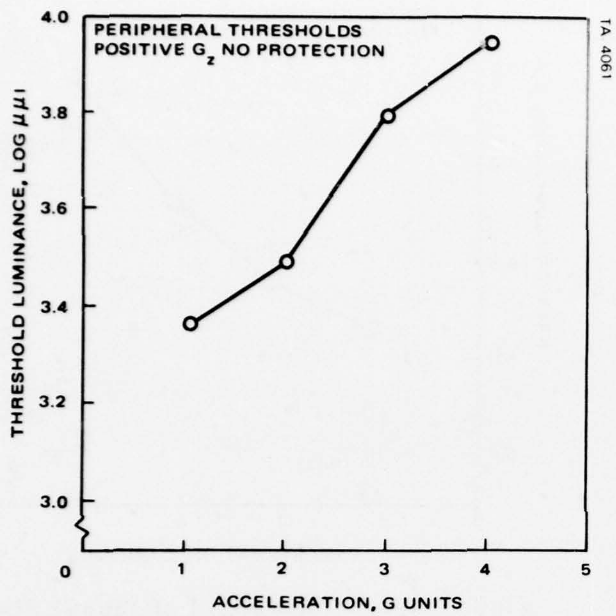

Figure 4-4. Threshold of peripheral vision under +1 to +4 G acceleration (After White, 1960).

(Warwick and Lund, 1946; White and Riley, 1958) accompanying increasing acceleration. Evidence that these phenomena also are explainable by a threshold shift is provided by an examination of the effects of illumination level on performance under acceleration.

Both contrast thresholds and visual acuity functions are dependent upon total amount of luminous energy (which determines the adaptation level of the eye). The decrease in visual sensitivity postulated to occur with acceleration can be likened to that occasioned by low levels of illumination. Thus, if the effects of acceleration on contrast thresholds, dial reading, and visual acuity are indeed the result of such a threshold shift, one would expect that deteriorating visual performance during acceleration could be compensated for by increasing the level of illumination. In fact, this is precisely what happens. The minimum discernible differential intensity (ΔI) is smaller (Braunstein and White, 1962), visual acuity is greater (White and Felder, 1958), and the number of dial reading errors is less (White and Riley, 1958) for a given acceleration level as stimulus and/or background illumination is increased up to a point, beyond which little additional improvement is evidenced.

Given that several related visual symptoms of acceleration appear to be explainable by a shift in the absolute visual threshold under accelerative stress, the next question concerns the origin of this effect. The literature indicates the shift in visual threshold is a result of retinal hypoxia (lack

of oxygen). Such a conclusion was partially supported by the similarity in responses of visual functions to acceleration and experimentally-induced hypoxia. Thus, not only were elevations of absolute visual thresholds reported under reduced oxygen conditions (McFarland and Evans, 1939; McFarland and Forbes, 1940), but investigations of visual acuity under low oxygen tension showed that hypoxia produced less and less visual decrement as luminance values increased (Berger, McFarland, Halperin and Niven, 1943).

Both the cause and severity of retinal hypoxia vary depending upon the orientation of the acceleration with respect to the axes of the body. In G_z acceleration, severe hypoxia results from acceleration-induced hemodynamic changes which cause reduced blood pressure, and thus oxygen transport, to the head region. During positive G_z acceleration, there is a decrease in blood pressure at the head as inertial force causes pooling of blood in the lower extremities (Gauer, 1961). During negative G_z acceleration, initial blood volume increase at the head triggers a reflexive lowering of heart rate and vasodilation causing lowered arterial pressure (Sieker, 1961) which, when coupled with the high venous pressure, again leads to impaired head level circulation (Gamble, Shaw, Henry and Gauer, 1949; Gauer and Zuidema, 1961).

Several investigators have provided evidence that acceleration-induced visual symptoms are the result of hypoxia affecting the retina. Lambert (1945) and Lambert and Wood (1946) provided early experimental evidence on the role of retinal circulation in producing blackout. Since intraocular pressure is approximately 20mm higher than intracerebral pressure, retinal circulation typically fails before cerebral circulation, and the visual symptoms of grayout and blackout become manifest under accelerative stress before unconsciousness occurs. By neutralizing intraocular pressure with suction goggles placed over the eyes, these investigators were able to prevent the occurrence of blackout previous to loss of consciousness during exposure to positive G_z acceleration. Conversely, applying a positive pressure to the eyes resulted in a lowering of the acceleration level at which blackout occurred.

Even more recently, investigators, by observing the retina (Duane, 1954), and conducting retinal photography and fluorescence angiography during

centrifugation (Leverett, Kirkland, Schermerhorn, and Newsom, 1967; Newsom, Leverett and Kirkland, 1968), have been able to correlate the visual symptoms of grayout and blackout with the observed decline and failure of retinal circulation. The additional observations that visual symptoms can be reduced by the normal and positive pressure breathing of pure O_2 (Chambers and Keer, 1962), and that concomitant general hypoxia decreases grayout and blackout thresholds (Burgess, 1958), highlights the fact that it is specifically the disruption of the oxygen transport function of the blood, and the resulting retinal hypoxia, that is the crucial factor causing visual disturbances during impaired retinal circulation.

G_x Acceleration

In G_x acceleration, the inertial force does not affect overall blood distribution. In this case, retinal hypoxia results from reduced oxygenation of arterial blood which occurs due to breathing difficulties encountered with increased pressure on the chest and disturbances of pulmonary circulation and thus gas exchange (Gauer and Bondurant, 1961).

The hypoxia developed under G_x stress, however, is apparently not as severe as that experienced under G_z acceleration, since the associated visual symptoms are not manifest until much higher G levels are obtained. More specifically, the visual symptoms associated with 2-5 G's in the G_z axis are not manifest during transverse acceleration until the acceleration magnitude reaches approximately 12 G's (Gauer and Ruff, 1939) with blackout occurring above 14G (Bührlen, 1937).

While the primary mechanism causing disruption of vision under accelerative stress appears to be retinal hypoxia, there is also some evidence that acceleration affects visual acuity by causing various types of mechanical interference with the eye. Thus, for example, blurring of vision during negative G_z acceleration has been directly related to excessive tearing (Smedal, et al, 1963). Also, the phenomenon of red out (or red vision), which is sometimes observed under $-G_z$ conditions, has been related to obstruction of vision by the conjunctive of the lower lid, which tends to gravitate over the eye under such conditions (White,

1961). In addition, the fact that decreases in visual functioning cannot be completely compensated by increased illumination suggests some additional factors may be operative.

One intuitively appealing hypothesis is that the inertial forces resulting from acceleration cause physical deformation of the eye and its structures, thus interfering with proper image formation. Some evidence for the existence of such an effect was provided by Beckman (reported by Smedal, et al, 1961). When a nearsighted person (-4 diopters myopia) was exposed to +8 G_x, he reported that the lines on an oscilloscope which were blurred at 1G became sharper in outlined at 8 G's. Smedal et al (1961) interpreted this to mean that the entire globe of the eye had been deformed, thus bringing the image into focus on the retina.

In order to ascertain the importance of mechanical ocular deformation factors, one might measure the effect of various opthalmic lenses on visual acuity under acceleration. Any acuity improvement noted under such conditions would not be attributable to improved oxygen transport, but rather to correction of some type of acceleration-induced refractive error.

Although quantitative data is not available to substantiate the hypothesis, it appears that some degree of "distraction" may occur under acceleration, triggered by sensations of pain, fear, and anxiety. During $+G_z$ acceleration visual capabilities deteriorate. With $-G_z$ acceleration, throbbing and congestion of the head, tearing, and headaches are reported. During transverse acceleration discomfort, pain, and breathing difficulty are experienced. It is undoubtedly true, however, that individuals vary in their subjective tolerance to acceleration just as they do in their objectively determined thresholds.

4.4.6 Vision Protection Under Acceleration: Summary and Recommendations

Body Position

As stated previously, the direction of application of G forces with respect to the body axes is an extremely important determinant of resulting visual effects. Since visual symptoms occur at much higher G load levels for G_x than for G_z acceleration, some degree of vision protection can be provided by manipulating body position. For example, in prone or supine positions, inertial force vectors associated with

aircraft turns and dives are directed through the G_x axis rather than through the G_z axis, as occurs in the seated position. However, consideration must be given to the practicality of such body positions with reference to the proper operation of displays and controls in the operational aircraft.

Acceleration Rise Rate

Also mentioned previously was the importance of acceleration rise rate in determining visual symptoms. Onset rate is especially critical during G_z acceleration, when visual symptoms are directly related to blood distribution. With slow onset rates, blackout can be avoided because the physiological reflect mechanisms of the body have time to compensate for the drop in head level blood pressure before severe retinal hypoxia sets in (Gauer and Henry, 1953). With rapid acceleration rates, vision may deteriorate to blackout (depending upon the maximum acceleration magnitude and duration) but may also return during continued acceleration as the reflexive compensatory mechanisms "catch up" (White, 1961). Figure 4-5 (Gauer and Henry, 1953) shows some combinations of maximum acceleration onset rates, and durations which can be achieved without causing blackout.

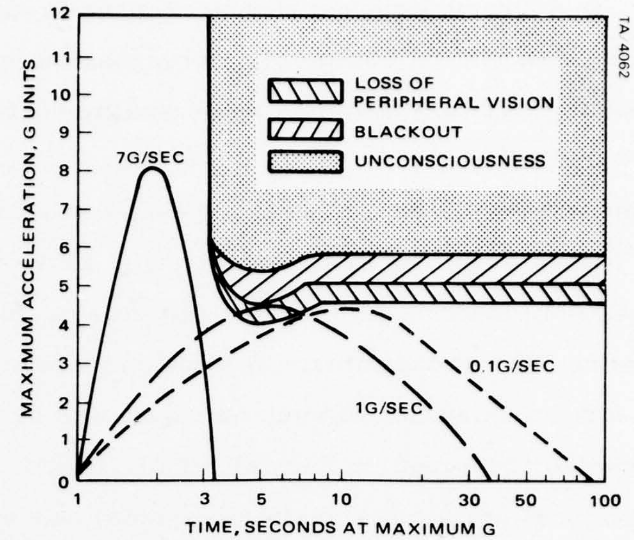

Figure 4-5. Acceleration onset rate, maximum acceleration and time at maximum G required to produce visual symptoms and unconsciousness (Gaver and Zuidema, 1961).

For several reasons, the appearance of visual symptoms always lags slightly behind the application of accelerative forces. First, the inertia of the blood mass prevents an instantaneous drop in head level

blood pressure with the onset of acceleration. Also, the inherent oxygen store of the cells prevents instantaneous retinal hypoxia even in the presence of lowered blood pressure. Further, the onset of the reflexive compensatory mechanisms takes time to be initiated. An important implication of these time lags in the operational setting is that visual disturbances may not be manifest until after acceleration has ceased in cases where onset rate was high and duration of acceleration short.

Vision Protection With G-suits, Central Display Placement, Increased Luminance Levels, and Increased Displayed Information Subtense

Assuming that visual effects observed under acceleration are caused primarily by a retinal hypoxia-induced shift in visual threshold, several methods of vision protection are suggested. One technique, already employed, involves utilization of the anti-G suit which, by applying blood pressure during G_z acceleration. In addition, there appear to be at least three other potential methods for protecting vision which are directly relevant to sensor system design.

4.5 MAINTAINING VISUAL CAPABILITIES UNDER ACCELERATION STRESS: DESIGN RECOMMENDATIONS

4.5.1 Compensate for Acceleration-Induced Decrease in Visual Field, Position Display Centrally

Acceleration at certain magnitudes has been shown to cause gross disturbances in visual functioning known as grayout (loss of peripheral vision) and blackout (loss of foveal as well as peripheral vision while retaining consciousness). For positive G_z acceleration gray out occurs (in unprotected subjects) at 4.1 ±0.7 G's, with blackout at 4.7 ±0.8 G's (Cochran, Gard, and Norsworthy, 1954). With transverse acceleration, visual symptoms occur much later, beginning above 12 G's (Clark et al, 1945; Code, Wood and Lambert, 1945; Grauer, 1950; Martin and Henry, 1950) with blackout above 14 G's (White, 1961). Because of the successive narrowing of the visual field that occurs with grayout and blackout, central positioning of sensor displays seems advisable.

It is suggested in the acceleration effects literature review that neither grayout nor blackout are caused by absolute visual receptor failure, but rather are the

result of a shift in receptor sensitivity. Thus it may be possible to maintain visibility of a peripherally-positioned display by increasing the intensity of displayed information. However, since such an alternative may increase display power requirements and have an adverse effect on operator dark adaption during night flights, the option of central positioning seems preferable.

Significant changes in visual functioning that can affect the visibility of display-presented sensor information occur long before blackout level is reached; visual acuity degrades, contrast perception decreases and absolute visual sensitivity declines. Some protection against such decrements can be provided by increasing the size and/or contrast of displayed information and/or increasing the level of background illumination.

4.5.2 Compensate for Decrements in Visual Acuity-Increase the Subtense of Displayed Information

Visual acuity refers to the ability to discriminate fine detail in the visual field and is defined as the smallest unit discernible by the eye; more specifically as "the reciprocal of the angle in minutes of arc subtended by the smallest detail which can be resolved by the human eye under a given set of viewing conditions" (Semple, et al, 1971, p. 245). Practically speaking, visual acuity can be seen as a measure of the human response capability to the resolution present in an image. For an operator to utilize the target information presented in a line-scanned sensor image, he must be able to resolve this information.

Research has revealed that visual acuity is degraded under accelerative stress. White and Jorve (1956) assessed binocular, right and left eye acuity at near and far effective viewing distances with a Bausch and Lomb Ortho-Rater. By manipulating the body position of the subjects with respect to the axis of acceleration, they were able to investigate the effects of positive and negative G_x and positive G_z forces. When in the seated position (experiencing $+G_z$ acceleration), all subjects wore the standard Air Force-Navy G-4A g suit which raised the average blackout threshold by 1.7 G's so that accelerations up to 5 Gs could be tested. Accelerations up to 8 Gs were examined in the transverse (G_x) axis. Table IV-1 presents a synthesis of the results of this study, transformed to indicate the increase

Table IV-1. Magnification required under accelerative stress to maintain binocular acuity at static (+1 G_z) level. (Magnification factors reported are based on averaged near and far acuity scores).

Acceleration level (G)		Magnification required for equivalent 1G performance
G_z	2	1.10
	3	1.19
	4	1.30
	5	1.44
G_x	6	1.60
	7	1.65
	8	2.07

in visual target subtense required under accelerative stress to maintain binocular acuity at static (+1 G_z) levels.

Increasing the size of displayed information is one way to compensate for the observed loss of acuity under acceleration, regardless of the origin of this loss. Thus, whether the visual acuity decrement is a result of mechanical deformation of the eye due to accelerative force or to an acceleration-induced shift in absolute visual sensitivity, some degree of vision protection can be provided by increasing image size. From the standpoint of sensor system design, such an increase could be accomplished by increasing overall display size and/or by reducing the sensor field of view.

The recommended magnification factors presented in Table IV-2, provide a useful estimate for required size increases under acceleration but are not universally applicable. These values represent the size increases required to maintain performance only under the specific conditions of contrast and luminance

Table IV-2. Increase in visual stimulus* required to perceive a stimulus as equaling that at +1 G_z (P=50 percent).

Acceleration (+G_z)	Fovea (no protection)	Periphery: No Protection	Periphery: CSU-3/P Anti-G Suit	Periphery: Full Bladder Suit
1	1	1	Valve opens at 2.4G and above	
2	1.26	1.38		
3	1.82	2.75	1.66	2.00
4	3.39	3.72	2.19	2.04

*Expressed as a ratio of that at +1 G_z

investigated (these values were not reported). As is well known in psychophysical research, acuity is affected by both contrast and luminance levels. Fine structural details cannot be discerned if the gray shade variations which define them are below the differential sensitivity of the eye, and this contrast sensitivity is in turn affected by the total amount of luminance energy. The higher the overall luminance, (i. e. the higher the adaptation level of the eye), the smaller the difference in intensity which can be perceived. Thus one must also consider the effects of acceleration on absolute and contrast sensitivity.

4.5.3 Compensate for Decrease in Visual Sensitivity-Increase Display Luminance and/or Contrast

There is considerable evidence that acceleration affects visual functioning by causing a decrease in absolute visual sensitivity (see acceleration Literature Review section of this report). Using the psychophysical method of limits, White (1960) was able to measure absolute foveal and peripheral thresholds under acceleration. Peripheral thresholds were determined with and without G-suit protection. Table IV-2 presents the results of this study transformed to indicate the increase in stimulus intensity required under acceleration to maintain threshold at static (+1 G_z) level. Unfortunately, the results were based on only one subject.

The data in Table IV-2 suggests that the acceleration-induced decrease in visual sensitivity can be partially compensated by making the displayed information brighter. As indicated previously, any decline in visual sensitivity can also be expected to affect acuity. The fact that the acceleration-induced reduction in sensitivity can be compensated by increasing stimulus intensity suggests indirectly that the visual acuity reduction occurring with acceleration may also be compensated by increasing stimulus intensity. Some additional evidence for this conclusion is provided by White and Riley (1958). Investigating the effects of $+G_z$ acceleration on the number of reading errors in a dial reading task, these investigators observed an interaction between acceleration and dial luminance (Figure 4-6). As can be seen from the figure, reading errors for all levels of acceleration were progressively reduced as luminance increased. Although dial reading is not a visual acuity in a strict sense, there

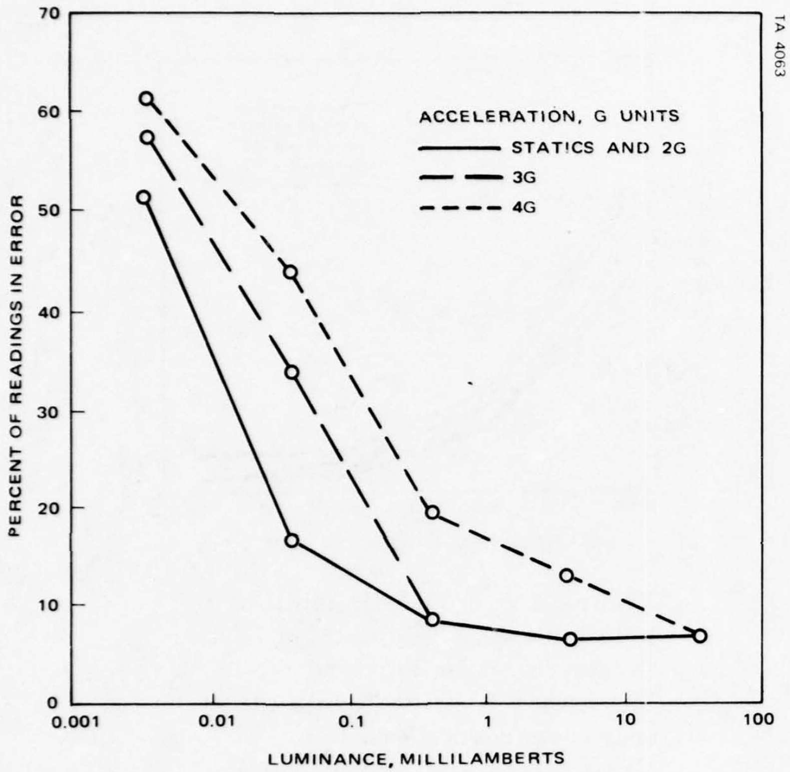

Figure 4-6. Percent of readings in error as a function of luminance level for each G value. The data show that the intensity of illumination could compensate for the decline of visual performance with acceleration.

are some definite similarities as both require the discrimination of fine details.

Results of the above reported studies indicate that the decline in absolute visual sensitivity caused by acceleration can be partially compensated by increasing the stimulus intensity. There is also evidence that the related decline in contrast sensitivity can be compensated either by increasing the contrast itself or by increasing the background luminance. The latter procedure increases the differential sensitivity of the eye by changing its adaptation level. Figures 4-7 and 4-8 present the results of a study designed to determine the effect of acceleration and background luminance level on contrast sensitivity (Braunstein and White, 1962). As expected from the psychophysical literature, the intensity ratio was for detection of a test patch of light varies inversely with the background intensity. Of special interest, however, is the fact that the decrease in contrast sensitivity caused by increasing levels of acceleration is considerably reduced at the higher background luminance levels. Again, considering the relationship between acuity, contrast, and luminance, Figures 4-7 and 4-8 can be interpreted as indicating that visual acuity under acceleration can

be partially protected by increasing display contrast and/or background luminance.

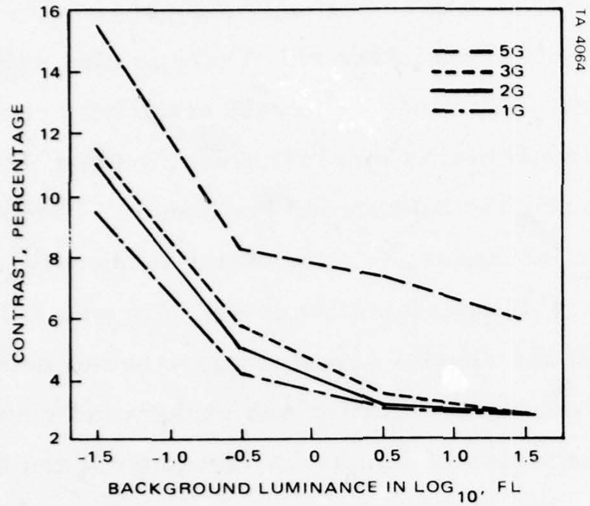

Figure 4-7. Relationship of brightness discrimination threshold to background luminance for four levels of positive acceleration (Braunstein and White, 1962).

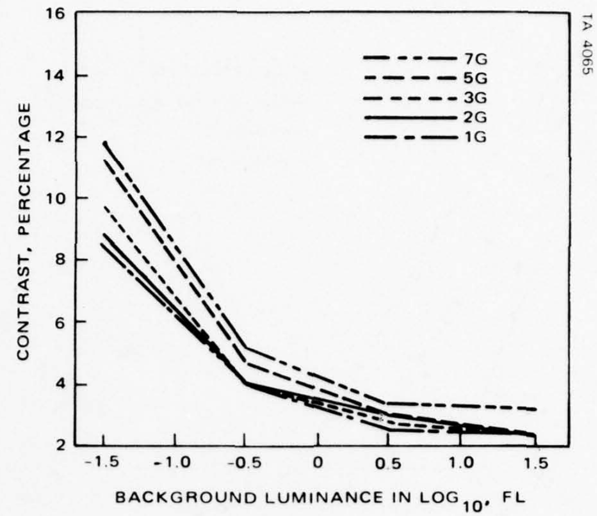

Figure 4-8. Relationship of brightness discrimination threshold to background luminance for five levels of transverse acceleration (Braunstein and White, 1962).

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APPENDIX A

DISPLAY QUALITY MODEL AND COMPUTER PROGRAM

The mathematical model for a display quality index which is described in this Appendix is based on the premise that display quality is a monotonically increasing function of the total number of perceivable shades of gray within a specified spatial frequency band. The relationship is not one of proportionality, however; a logarithmic function gives numerical results which are in good agreement with subjective judgments by qualified observers. The problem at hand is to find the number of perceivable gray shades between specified spatial frequency limits as a function of many of the environmental and display variables which influence the perceptual process. The solution is straightforward.

At each spatial frequency within the band of interest, the visual demand modulation $M_D(f)$ of an observer is computed from a fourteen-term regression equation obtained through laboratory research (Rogers and Carel, 1973), and this modulation quantity is converted to a demand dynamic range $Z_D(f)$ via the relation $Z_D(f) = 1+M_D(f)/1-M_D(f)$. Similarly, the amount of modulation $M(f)$ observable from the display at each spatial frequency can be computed by finding its intrinsic modulation M_I and multiplying by the modulation transfer function value at the spatial frequency in question. This accounts for limitations in the phosphor response due to a noninfinitesimal spot size. The intrinsic modulation M_I is the observable modulation capability of the display at very low spatial frequency. The intrinsic modulation is found from $M_I = L_{MAX} - L_{MIN}/L_{MAX} + L_{MIN}$. Here L_{MAX} is the maximum luminance presentable to the observer by the display with a neutral density contrast enhancement filter (if any) in place. Finally, L_{MIN} is the minimum luminance presented to the observer, which is either the ambient illumination reflected from various display surfaces or subjective black, whichever is greater. The observable modulation $M(f)$ at each spatial frequency is likewise converted to observable dynamic range $Z(f)$ by $Z(f) = 1+M(f)/1-M(f)$.

At this point, we have obtained two comparable quantities. The first is $Z_D(f)$, the dynamic range required to perceive a shade of gray at a specific spatial frequency, and the second is $Z(f)$, the dynamic range which stimulates the observer at the same spatial

frequency. Because the perception of visual intensity is a logarithmic process, the ratio of the logarithms of these two quantities is indicative of the number $N(f)$ of theoretically perceivable gray shade intervals at the spatial frequency in question. We have $N(f) = 1 + \log Z(f)/\log Z_D(f)$. The total number of theoretically perceivable shades of gray between spatial frequencies f_B and f_T is then

$$N = \int_{f_B}^{f_T} N(f)df,$$

which we approximate by

$$N = \sum_{f=f_B}^{f_T} N(f).$$

The display quality index Q is taken to be $Q = \log_{10} N$.

The details of computing $M_D(f)$ are explained below. Rogers and Carel in 1973 derived the following regression equation for $\log_{10} M_D(f)$ as a function of four variables. Let $a = \log_{10} L_{DO}$, $b = \log_{10} L_S$, $c = \log_{10} S_S$, and $d = \log_{10} f$. Here L_{DO} is the observed average display luminance, equal to the average display luminance L_D times the contrast enhancement filter transmittance T in percent divided by 100. The average surround luminance is denoted by L_S, the angular subtense of the stimulus area in degrees is S_S, and the spatial frequency in cycles per degree is f. All luminance quantities are measured in footlamberts. Then the regression equation is $\log_{10} M_D(f) = -0.81120 - 0.31800\,a + 0.12219\,b - 1.62162\,c - 3.05375\,d + 0.15041\,a^2 + 0.10692\,b^2 + 0.02441\,c^2 + 2.26544\,d^2 - 0.19435\,ab - 0.01115\,ac - 0.16251\,ad - 0.10949\,bc - 0.03871\,bd + 1.24461\,cd$. The threshold for "barely perceiving" the presence of the modulation at spatial frequency f is obtained by rasing 10.0 to the power obtained from the regression equation. A factor of 1.6 is normally applied to the resulting marginal threshold value for "comfortably perceiving" the presence of the stimulus modulation.

The observable modulation M(f) at spatial frequency f is given by

$$M(f) = M_I\, e^{-f^2/2\sigma_f^2},$$

where M_I is the intrinsic modulation and σ_f is a parameter which defines the spatial frequency response properties of the phosphor. The parameter σ_f is related to the spotsize w as follows. If

w is the distance in mils between the 50% amplitude points of a Gaussian CRT spot, then $w = 2.35\ \sigma$, where σ is the spot radius in mils, and

$$\sigma_f = \frac{1}{2\pi\ \sigma/1000} = \frac{1}{2\pi\ w/2350}$$

has dimensions of cycles per inch. To convert to angular measure, we multiply by the viewing distance in inches and divide by the number of degree per radian, which converts the dimensions of σ_f to cycles per degree.

The intrinsic modulation M_I is given by $M_I = L_{MAX} - L_{MIN}/L_{MAX} + L_{MIN}$. The quantity L_{MAX} is the maximum luminance with which the display/filter combination can stimulate the observer. Thus, $L_{MAX} = B_{MAX}\ T/100$, where B_{MAX} is the maximum display luminance capability and T is the filter transmittance in percent. The parameter B_{MAX} is estimated from knowledge of the average display luminance L_D and the luminance level B_S of subjective black as follows. Approximating L_D by $B_{MAX} + B_{MIN})/2$, we obtain $B_{MAX} = 2L_D - B_{MIN}$, where B_{MIN} is the minimum brightness of the display. Now $B_{MIN}\ T/100 = B_S$ is the lowest luminance level useful to the observer, so we have $B_{MIN} = B_S/T/100$.

The luminance level of subjective black is computed as a function of the average surround luminance L_S from data measured by Pitt (1945) and by Nutting (1916). For $L_S \leq 50$ footlamberts, we have $\log_{10} B_S = 0.64 \log_{10} L_S - 1.9$, and for $L_S > 50$ footlamberts, we use $\log_{10} B_S = 0.988 \log_{10} L_S - 2.7$. The quantity L_{MIN} is the minimum luminance presented to the observer from the display/filter. Thus, L_{MIN} is either subjective black B_S or the luminance reflected from the filter front surface and the CRT phosphor with filter attenuation taken into account, whichever is greater. Let R_f be the first surface reflection coefficient in percent, and let R_p be the phosphor reflection coefficient in percent. Then the reflected ambient luminance L_R from the filter and the phosphor is given by

$$L_R = L_S \left[\left(\frac{R_p}{100}\right) \left(\frac{T}{100}\right)^2 \left(1 - \frac{R_f}{100}\right) + \frac{R_f}{100} \right],$$

and $L_{MIN} = MAX\ (B_S,\ L_R)$.

The foregoing paragraphs define the relationships among the display and environment variables incorporated into the gray shade model for display quality. This model has been put in the form of a computer program written in FØRTRAN for a Xerox Sigma 5

computer. The program listing and typical results appear at the end of this Appendix. The following paragraphs will describe how the program is used.

After the program is loaded, control is passed to the operator's keyboard and the program waits for imput data to be typed in. The list of legal type-in variables and their units is given in the comments at the beginning of the program. The default values are given on lines 36-46. These values are used unless changed by a subsequent type-in. For example, if the first type-in were "STIMLUM = 100.0, RPHØS = 75.0*", all the default values except those for STIMLUM and RPHØS would be used for the first run. If the second type-in (when the program returns control to the keyboard) were "RPHØS = 65.0*", the last previous value of STIMLUM, namely 100.0, would be used for the second run rather than the default value. Thus, only those parameters whose values are different from what they were on the last preceding trial need be typed in. Note also that the type-in is terminated by an asterisk (*). This character tells the INPUT processor that no more data is forthcoming for this trial, and the program then proceeds.

When the program has completed the computation, it outputs the conditions and results of the current trial on the line printer, and branches back to return control to the operator's keyboard. In this manner, an arbitrary number of trials can be made without reloading the program, and there need be no particular structure to the variation of parameters that is performed. If it is desired to execute a factorial investigation of a number of parameters, the INPUT statement on line 62 and the GØ TØ statement on line 206 may be replaced by an appropriate number of nested DØ loops and their terminations, respectively. The program running time is fairly short, with 225 iterations (a 5 x 5 x 3 x 3 factorial investigation of four parameters using four nested DØ loops) requiring less than three minutes of CPU time.

By using the program, a designer can find the best quality display among a number of alternate display mechanizations. Under different circumstances, he can quantitatively examine the effect on display quality of perturbations of baseline design parameter values. Such information is highly useful in engineering tradeoffs with cost, reliability, and other quantitative factors. Finally, with some additional software, a display designer could perform a constrained optimization and obtain a set of design values which results in the highest quality display which meets his environmental and physical constraints. Of course,

other display parameters such as size and color have not as yet been incorporated into the quality model, and at present it is really only applicable to CRT displays. The existing model is nonetheless a useful tool, and the processes of extension and refinement should continue.

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PROGRAM LISTING

```
*
C      DEFINE VARIABLES WHICH CAN BE TYPED IN AT RUN TIME.
C      ALL LUMINANCE QUANTITIES ARE IN FOOTLAMBERTS.
C      STIMLUM IS THE AVERAGE LUMINANCE OF THE DISPLAY WITHOUT ANY
C      CONTRAST ENHANCEMENT FILTER.
C      SURRLUM IS THE AVERAGE LUMINANCE OF THE SURROUNDING AMBIENT FIELD.
C      STIMSUB IS THE ANGULAR SUBTENSE OF THE STIMULUS FIELD IN DEGREES.
C      BOTLIM IS THE BOTTOM LIMIT OF INTEGRATION IN CYCLES PER DEGREE.
C      TOPLIM IS THE UPPER LIMIT OF INTEGRATION IN CYCLES PER DEGREE.
C      THESE DEFINE THE SPATIAL FREQUENCY LIMITS BETWEEN WHICH GREY
C      SHADES ARE COUNTED.
C      RPHOS IS THE PHOSPHOR REFLECTANCE IN PERCENT.
C      TFILT IS THE TRANSMISSIVITY OF A NEUTRAL DENSITY FILTER IN PERCENT.
C      FIRSTREF IS THE AMOUNT OF FIRST SURFACE REFLECTION OF AMBIENT
C      ILLUMINATION IN PERCENT.
C      SPOTSIZE IS THE CRT SPOT DIAMETER AT THE 50 PERCENT AMPLITUDE
C      (2.35 SIGMA) POINT IN MILS.
C      VUDIST IS THE VIEWING DISTANCE IN INCHES.
C      FUDGFACT IS A DIMENSIONLES FIELD FACTOR USED TO ACCOUNT FOR
C      DIFFERENCES IN MODULATION SENSITIVITY BETWEEN LABORATORY THRESHOLD
C      DATA AND ACTUAL FIELD CONDITIONS.
C      TFLAG IS A TERMINATION FLAG WHICH TELLS THE PROGRAM WHEN TO EXIT.
C      IF TFLAG IS ZERO OR NEGATIVE, THE PROGRAM STOPS.
*
       NAMELIST STIMLUM, SURRLUM, STIMSUB, BOTLIM, TOPLIM
       NAMELIST RPHOS, TFILT, FIRSTREF
       NAMELIST SPOTSIZE, VUDIST, FUDGFACT, TFLAG
       PI=3.141592653
       RAD=57.29577951
*
C      DEFAULT VALUES OF TYPE-IN VARIABLES.
C      THESE ARE USED UNLESS CHANGED BY OPERATOR AT INPUT.
C      ONCE CHANGED, THE NEW VALUES ARE USED UNTIL CHANGED BY A
C      SUBSEQUENT TYPE-IN.
*
       STIMLUM=50.0
       SURRLUM=50.0
       STIMSUB=4.0
       BOTLIM=2.0
       TOPLIM=30.0
       RPHOS=70.0
       TFILT=100.0
       FIRSTREF=0.5
       SPOTSIZE=10.0
       VUDIST=30.0
       FUDGFACT=1.6
       TFLAG=1.0
*
C      OUTPUTS PROMPTING MESSAGE TO THE OPERATOR'S KEYBOARD.
*
       WRITE(102,10)
    10 FORMAT(//,1X, *STIMLUM, SURRLUM, STIMSUB, BOTLIM, TOPLIM*)
       WRITE(102,11)
    11 FORMAT(1X, *RPHOS, TFILT, SPOTSIZE, VUDIST, FUDGFACT, TFLAG*)
       WRITE(102,12)
    12 FORMAT(1X, *FIRSTREF*)
*
C      THE KEYBOARD BECOMES ACTIVE AT THIS POINT, AND WAITS FOR THE
C      OPERATOR TO SPECIFY ANY NEW VALUES OF THE  NAMELIST  VARIABLES.
C      WHEN FINISHED, THE INPUT IS TERMINATED WITH AN ASTERISK (*).
*
    15 INPUT(101)
*
C      TEST TO SEE IF PROGRAM SHOULD STOP.
*
       IF(TFLAG.LE.0.0) GO TO 100
       IBOTLIM=INT(BOTLIM+0.5)
       ITOPLIM=INT(TOPLIM+0.5)
*
C      FIND THE LUMINANCE LEVEL OF SUBJECTIVE BLACK AS A FUNCTION OF THE
C      SURROUND LUMINANCE.
*
       BSUBJ=10.0**((0.64*ALOG10(SURRLUM))-1.9)
       IF(SURRLUM.GT.80) BSUBJ=10.0**((0.988*ALOG10(SURRLUM))-2.7)
*
C      ESTIMATE THE MAXIMUM LUMINANCE CAPABILITY OF THE CRT.
*
       BMAX=(2.0*STIMLUM)-(BSUBJ/(TFILT/100.0))
       IF(BMAX.LE.0.0) BMAX=BSUBJ/(TFILT/100.0)
*
C      THE MAXIMUM OBSERVED LUMINANCE IS THE MAXIMUM DISPLAYED LUMINANCE
C      ATTENUATED BY THE CONTRAST ENHANCEMENT FILTER.
*
       RLMAX=BMAX*TFILT/100.0
*
C      COMPUTE THE AMOUNT OF AMBIENT ILLUMINATION REFLECTED FROM VARIOUS
C      SURFACES OF THE CRT AND CONTRAST ENHANCEMENT FILTER.
*
       REFLECT=SURRLUM*(RPHOS/100.0)*(TFILT/100.0)*(TFILT/100.0)*(1.0-
      1(FIRSTREF/100.0)) + ((FIRSTREF/100.0)*SURRLUM)
*
C      THE MINIMUM OBSERVED LUMINANCE IS THAT REFLECTED FROM THE CRT OR
C      SUBJECTIVE BLACK, WHICHEVER IS GREATER.
*
       RLMIN=AMAX(BSUBJ, REFLECT)
       IF(RLMAX.LE.RLMIN) RLMAX=RLMIN
*
C      FIND THE AVAILABLE AMOUNT OF MODULATION
*
       AVLMOD=(RLMAX-RLMIN)/(RLMAX+RLMIN)
       RINPDEG=VUDIST/RAD
*
C      COMPUTE THE WIDTH OF THE SPATIAL FREQUENCY RESPONSE OF THE CRT DUE
C      TO THE GAUSSIAN SPOT. THE CRT MTF IS ALSO GAUSSIAN, WITH PARAMETER
C      SIGMAF DEFINING THE SPATIAL FREQUENCY AT WHICH THE MTF IS DOWN TO
C      60 PERCENT OF THE RESPONSE AT DC.
*
       SIGMAF=(1.0/((2.0*PI)*(SPOTSIZE/2350.0)))*RINPDEG
       SIGMAF2=SIGMAF*SIGMAF
*
C      COMPUTE VARIABLES USED IN THE REGRESSION EQUATION FOR MODULATION
C      SENSITIVITY AS A FUNCTION OF STIMULUS LUMINANCE, SURROUND
C      LUMINANCE, STIMULUS SUBTENSE, AND SPATIAL FREQUENCY.
*
       A=ALOG10(STIMLUM*TFILT/100.0)
       B=ALOG10(SURRLUM)
       C=ALOG10(STIMSUB)
       A2=A*A
       B2=B*B
       C2=C*C
       AB=A*B
       AC=A*C
       BC=B*C
       PARTMOD=-0.81190-0.31800*A+0.12210*B-1.62162*C+0.15041*A2+0.10692*
      1B2+0.02441*C2-0.19435*AB-0.01115*AC-0.10949*BC
       GREY=0.0
```

PROGRAM LISTING (Continued)

```
      *
      C     THIS LOOP COMPUTES THE AVAILABLE DYNAMIC RANGE AND THE DEMAND
      C     DYNAMIC RANGE AT EACH SPATIAL FREQUENCY, AND FROM THESE DETERMINES
      C     AND ACCUMULATES THE NUMBER OF THEORETICALLY PERCEIVABLE SHADES OF
      C     GREY. THE LOGARITHM OF THIS NUMBER IS AN INDEX OF THE DISPLAY
      C     QUALITY.
      *
            DO 20 I=IBOTLIM,ITOPLIM
            F=FLOAT(I)
            D=ALOG10(F)
      *
      C     FIND THE AMOUNT OF MODULATION PRODUCED BY THE DISPLAY AT THIS
      C     SPATIAL FREQUENCY.
      *
            RLMOD=AVLMOD*EXP((-F*F)/(2.0*SIGMAF2))
      *
      C     CONVERT MODULATION TO DYNAMIC RANGE.
      *
            AVLDR=(1.0+RLMOD)/(1.0-RLMOD)
      *
      C     COMPUTE THE VISUAL DEMAND MODULATION FROM THE REMAINING TERMS OF
      C     THE REGRESSION EQUATION.
      *
            FULLMOD=PARTMOD-3.05375*D+2.26544*D*D-0.16251*A*D-0.03871*B*D+
           11.24461*C*D
            DEMMOD=(10.0**(FULLMOD))*FUDGFACT
      *
      C     DEMAND MODULATION GREATER THAN 1.0 INDICATES EITHER THE REGRESSION
      C     EQUATION IS NOT VALID FOR THE SPECIFIED CONDITIONS OR THE EYE
      C     CANNOT PERCEIVE ANY INTENSITY MODULATION UNDER THE SPECIFIED
      C     CONDITIONS.
      *
            IF(DEMMOD.GE.1.0) WRITE(108,16); GO TO 20
         16 FORMAT(11X, *DEMAND MODULATION HAS EXCEEDED 100 PERCENT*)
      *
      C     CONVERT MODULATION TO DEMAND DYNAMIC RANGE.
      *
            DEMDR=(1.0+DEMMOD)/(1.0-DEMMOD)
      *
      C     COMPUTE THE THEORETICAL NUMBER OF LOGARITHMIC SHADES OF GREY IN
      C     THE AVAILABLE DYNAMIC RANGE AT THIS SPATIAL FREQUENCY.
      *
            PARTGREY=1.0+(ALOG10(AVLDR))/ALOG10(DEMDR)
            IF(PARTGREY.LE.1.0) PARTGREY=0.0
      *
      C     ACCUMULATE THE TOTAL NUMBER OF GREY SHADES.
      *
            GREY=GREY+PARTGREY
         20 CONTINUE
            IGREY=INT(GREY+0.5)
      *
      C     COMPUTE THE INDEX OF DISPLAY QUALITY.
      *
            IF(IGREY.LE.0) RINDEX=0.0; GO TO 25
            RINDEX=ALOG10(FLOAT(IGREY))
      *
      C     PRINT OUT THE CONDITIONS AND RESULTS OF THE COMPUTATION.
      *
         25 WRITE(108,30) STIMLUM, SURRLUM, STIMSUB, STIMLUM*TFILT/100.0,
           1SPOTSIZE, VUDIST, FIRSTREF, RPHOS, TFILT, FUDGFACT
         30 FORMAT(1H1, 10X, *AVERAGE DISPLAY LUMINANCE =*, F8.3, * FOOTLAMBE
           1RTS*,/, 11X, *AVERAGE SURROUND LUMINANCE =*, F8.3, * FOOTLAMBERTS*
           2,/, 11X, *STIMULUS SUBTENSE =*, F8.3, * DEGREES*,/, 11X, *AVERAGE
           3FILTERED LUMINANCE =*, F8.3, * FOOTLAMBERTS*,/, 11X, *SPOTSIZE =*,
           4 F8.3, * MILS*,/, 11X, *VIEWING DISTANCE =*, F8.3, * INCHES*,/,
           511X, *FIRST SURFACE REFLECTION COEFFICIENT =*, F8.3, * PERCENT*,/,
           611X, *PHOSPHOR REFLECTANCE =*, F8.3, * PERCENT*,/, 11X, *FILTER TR
           7ANSMITTANCE =*, F8.3, * PERCENT*,/, 11X, *FIELD FACTOR =*, F8.3)
            WRITE (108,35) AVLMOD*100.0, SIGMAF*1.17
         35 FORMAT(11X, *AVAILABLE MODULATION =*, F8.3, * PERCENT*,/, 11X,
           1*SPATIAL FREQUENCY FOR WHICH MTF IS 50 PERCENT =*, F8.3, * CYCLES
           2PER DEGREE*)
            WRITE(108,40) BOTLIM, TOPLIM, IGREY
         40 FORMAT(/, /, 11X, *THE NUMBER OF PERCEIVABLE GREY SHADES *,/, 11X,
           1*BETWEEN *, F5.2, * AND *, F5.2, * CYCLES PER DEGREE IS *, I5)
            WRITE(108,50) RINDEX
         50 FORMAT(/, 11X, *THE DISPLAY QUALITY INDEX IS *, F7.4)
            WRITE(108,60)
         60 FORMAT(1X,/,/,/,/,/)
            GO TO 15
        100 STOP
            END
```

TYPICAL RESULTS

```
AVERAGE DISPLAY LUMINANCE =  50.000 FOOTLAMBERTS
AVERAGE SURROUND LUMINANCE =  50.000 FOOTLAMBERTS
STIMULUS SUBTENSE =   4.000 DEGREES
AVERAGE FILTERED LUMINANCE =   5.000 FOOTLAMBERTS
SPOTSIZE =  10.000 MILS
VIEWING DISTANCE =  30.000 INCHES
FIRST SURFACE REFLECTION COEFFICIENT =     .500 PERCENT
PHOSPHOR REFLECTANCE =  70.000 PERCENT
FILTER TRANSMITTANCE =  10.000 PERCENT
FIELD FACTOR =   1.600
AVAILABLE MODULATION =  88.564 PERCENT
SPATIAL FREQUENCY FOR WHICH MTF IS 50 PERCENT =  22.912 CYCLES PER DEGREE

THE NUMBER OF PERCEIVABLE GREY SHADES
BETWEEN  2.00 AND 30.00 CYCLES PER DEGREE IS  1597

THE DISPLAY QUALITY INDEX IS  3.2033
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AVERAGE DISPLAY LUMINANCE =  50.000 FOOTLAMBERTS
AVERAGE SURROUND LUMINANCE =  50.000 FOOTLAMBERTS
STIMULUS SUBTENSE =   4.000 DEGREES
AVERAGE FILTERED LUMINANCE =  10.000 FOOTLAMBERTS
SPOTSIZE =  10.000 MILS
VIEWING DISTANCE =  30.000 INCHES
FIRST SURFACE REFLECTION COEFFICIENT =     .500 PERCENT
PHOSPHOR REFLECTANCE =  70.000 PERCENT
FILTER TRANSMITTANCE =  20.000 PERCENT
FIELD FACTOR =   1.600
AVAILABLE MODULATION =  86.708 PERCENT
SPATIAL FREQUENCY FOR WHICH MTF IS 50 PERCENT =  22.912 CYCLES PER DEGREE

THE NUMBER OF PERCEIVABLE GREY SHADES
BETWEEN  2.00 AND 30.00 CYCLES PER DEGREE IS  2068

THE DISPLAY QUALITY INDEX IS  3.3155
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AVERAGE DISPLAY LUMINANCE = 100.000 FOOTLAMBERTS
AVERAGE SURROUND LUMINANCE =  50.000 FOOTLAMBERTS
STIMULUS SUBTENSE =   4.000 DEGREES
AVERAGE FILTERED LUMINANCE =  10.000 FOOTLAMBERTS
SPOTSIZE =  10.000 MILS
VIEWING DISTANCE =  30.000 INCHES
FIRST SURFACE REFLECTION COEFFICIENT =     .500 PERCENT
PHOSPHOR REFLECTANCE =  70.000 PERCENT
FILTER TRANSMITTANCE =  10.000 PERCENT
FIELD FACTOR =   1.600
AVAILABLE MODULATION =  94.148 PERCENT
SPATIAL FREQUENCY FOR WHICH MTF IS 50 PERCENT =  22.912 CYCLES PER DEGREE

THE NUMBER OF PERCEIVABLE GREY SHADES
BETWEEN  2.00 AND 30.00 CYCLES PER DEGREE IS  2685

THE DISPLAY QUALITY INDEX IS  3.4989
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AVERAGE DISPLAY LUMINANCE =  50.000 FOOTLAMBERTS
AVERAGE SURROUND LUMINANCE =  50.000 FOOTLAMBERTS
STIMULUS SUBTENSE =   4.000 DEGREES
AVERAGE FILTERED LUMINANCE =  50.000 FOOTLAMBERTS
SPOTSIZE =  10.000 MILS
VIEWING DISTANCE =  30.000 INCHES
FIRST SURFACE REFLECTION COEFFICIENT =     .500 PERCENT
PHOSPHOR REFLECTANCE =  70.000 PERCENT
FILTER TRANSMITTANCE = 100.000 PERCENT
FIELD FACTOR =   1.600
AVAILABLE MODULATION =  48.007 PERCENT
SPATIAL FREQUENCY FOR WHICH MTF IS 50 PERCENT =  22.912 CYCLES PER DEGREE

THE NUMBER OF PERCEIVABLE GREY SHADES
BETWEEN  2.00 AND 30.00 CYCLES PER DEGREE IS  1691

THE DISPLAY QUALITY INDEX IS  3.2981
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